HETEROGENEOUS SHALLOW-SHELF CARBONATE BUILDUPS IN THE PARADOX BASIN, UTAH AND COLORADO: TARGETS FOR INCREASED OIL PRODUCTION AND RESERVES USING HORIZONTAL DRILLING TECHNIQUES

SEMI-ANNUAL TECHNICAL PROGRESS REPORT October 6, 2003 - April 5, 2004

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Thomas C. Chidsey, Jr., Principal Investigator/Program Manager,
and Sharon Wakefield,
Utah Geological Survey,
and
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UTAH GEOLOGICAL SURVEY

July 2004

Contract No. DE-FC26-00BC15128

Gary D. Walker, Contract Manager
U.S. Department of Energy
National Petroleum Technology Office
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ABSTRACT

The Paradox Basin of Utah, Colorado, Arizona, and New Mexico contains nearly 100 small oil fields producing from carbonate buildups within the Pennsylvanian (Desmoinesian) Paradox Formation. These fields typically have one to 10 wells with primary production ranging from 700,000 to 2,000,000 barrels (111,300-318,000 m^3) of oil per field and a 15 to 20 percent recovery rate. At least 200 million barrels (31.8 million m^3) of oil will not be recovered from these small fields because of inefficient recovery practices and undrained heterogeneous reservoirs.

Several fields in southeastern Utah and southwestern Colorado are being evaluated as candidates for horizontal drilling and enhanced oil recovery from existing vertical wells based upon geological characterization and reservoir modeling case studies. Geological characterization on a local scale is focused on reservoir heterogeneity, quality, and lateral continuity, as well as possible reservoir compartmentalization, within these fields. This study utilizes representative cores, geophysical logs, and thin sections to characterize and grade each field's potential for drilling horizontal laterals from existing development wells. The results of these studies can be applied to similar fields elsewhere in the Paradox Basin and the Rocky Mountain region, the Michigan and Illinois Basins, and the Midcontinent region.

This report covers research activities for the second half of the fourth project year (October 6, 2003 through April 5, 2004). The work included preparing (1) three-dimensional reservoir models and (2) reservoir calculations from Cherokee and Bug fields, San Juan County, Utah. Cherokee field three-dimensional (3-D) diagrams with structural contours on top of the upper and lower Ismay zone and Gothic shale show the same general southwest-dipping structural nose upon which the carbonate buildup and reservoir developed. Cherokee wells that contain phylloid-algal buildups and lie along the edge of thick anhydrite follow the regional, upper Ismay facies pattern where intrashelf basins contain thick anhydrite accumulations. Three-dimensional models of the thickness of Ismay intervals display a general west-northwest to east-southeast trend, punctuated by elongate to slightly equant thicks. Five reservoir porosity units with porosity greater than 6 percent are present in the upper Ismay. These porosity units represent the phylloid-algal buildups and, as typical of the upper Ismay trend in the Blanding sub-basin, are viewed in 3-D as small equant-shaped pods. The 3-D thickness diagrams suggest all five porosity units have an untested northeastern area.

Bug field 3-D diagrams with structural contours on top of the lower Desert Creek zone and Chimney Rock shale show southwest regional dip and a subtle, elongate, northwest-southeast-trending anticline. A 3-D model of the entire thickness of the Desert Creek zone likewise displays the same general northwest-southeast trend, as do the structural diagrams, with elongate thins and thicks depicting the typical nearshore shoreline linear facies tracts of the Desert Creek zone in the northern Blanding sub-basin. Three-dimensional diagrams of the lower Desert Creek depicting the net feet of porosity greater than 10 and 12 percent show the porosity pinches out along the northeast flank of the buildup, which when combined with the top of the lower Desert Creek displays a combination stratigraphic/structural trap.

Volumes (in acre-feet) were calculated for the Cherokee and Bug field reservoirs. For Cherokee field, the total volume of the reservoir porosity units is 17,522 acre-feet, and may contain over 350,000 barrels of oil (BO) and 6.6 billion cubic of gas (BCFG) primary recovery. Based on these calculations, the remaining recoverable oil and gas reserves are nearly 168,000 BO and 3 BCFG, suggesting the presence of additional undrained zones. Using a price of $30/

bbl and $4/MCFG, the unrisked value of the remaining recoverable reserves is over $5 million and $11 million for oil and gas, respectively. For Bug field, the volume calculated for net feet of porosity greater than 10 percent is 99,057 acre-feet. This also suggests the presence of additional undrained zones. The lower Desert Creek may contain recoverable oil and gas reserves of nearly 2,440,000 BO and 5.7 BCFG. Again, using $30/BO and $4/MCFG oil and gas prices, the unrisked value of the remaining reserves is over $73 million and $22 million for oil and gas, respectively.

Technology transfer activities for the reporting period consisted of technical presentations and publications. The project home page was updated on the Utah Geological Survey Web site.

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EXECUTIVE SUMMARY

The project's primary objective is to enhance domestic petroleum production by demonstration and transfer of horizontal drilling technology in the Paradox Basin of Utah and Colorado. If this project can demonstrate technical and economic feasibility, then the technique can be applied to approximately 100 additional small fields in the Paradox Basin alone, and result in increased recovery of 25 to 50 million barrels (4-8 million m^3) of oil. This project is designed to characterize several shallow-shelf, carbonate reservoirs in the Pennsylvanian (Desmoinesian) Paradox Formation, choose the best candidate field(s) for a pilot demonstration project to drill horizontally from existing vertical wells, monitor well performance(s), and report associated validation activities.

The Utah Geological Survey heads a multidisciplinary team to determine the geological and reservoir characteristics of typical, small, shallow-shelf, carbonate reservoirs in the Paradox Basin. The Paradox Basin technical team consists of the Utah Geological Survey (prime contractor), Colorado Geological Survey (subcontractor), Eby Petrography & Consulting Inc. (subcontractor), and Seeley Oil Company (subcontractor and industry partner). This research is funded by the Class II Oil Revisit Program of the U.S. Department of Energy, National Petroleum Technology Office (NPTO) in Tulsa, Oklahoma. This report covers research activities for the second half of the fourth project year (October 6, 2003, through April 5, 2004). This work included preparing (1) three-dimensional (3-D) reservoir models and (2) reservoir calculations from Cherokee and Bug fields, San Juan County, Utah. From these and other project evaluations, untested or under-produced reservoir compartments and trends can be identified as targets for horizontal drilling. The results of this study can be applied to similar reservoirs in many U.S. basins.

Cherokee field 3-D diagrams with structural contours on top of the upper and lower Ismay zone and Gothic shale show the same general southwest-dipping structural nose upon which the carbonate buildup reservoir developed. There is an abrupt end of the structure suggesting the possible presence of a normal fault where late-stage microporosity may have developed. Cherokee wells that contain phylloid-algal buildups and lie along the edge of thick anhydrite follow the regional, upper Ismay facies pattern where intrashelf basins contain thick anhydrite accumulations. Phylloid-algal buildups developed on innershelf and tidal flats within curvilinear bands that rim the intrashelf basins. Three-dimensional models of the thickness of the entire Ismay zone, upper Ismay, lower Ismay, and upper Ismay clean carbonate, display a general west-northwest to east-southeast trend, punctuated by elongate to slightly equant thicks. Five reservoir porosity units with porosity greater than 6 percent are present in the upper Ismay mound and separated from each other by low-porosity/permeability barriers. These porosity units represent the phylloid-algal buildups and, typical of the upper-Ismay trend in the Blanding sub-basin, are viewed in 3-D as small equant-shaped pods. Porosity unit 5 is the largest and most likely the major production contributor, as well as holding the bulk of the remaining reserves. The 3-D thickness diagrams suggest all five porosity units have an untested northeastern area.

Bug field 3-D diagrams with structural contours on top of the lower Desert Creek zone and Chimney Rock shale show a southwest regional dip and a subtle, elongate, northwest-southeast-trending anticline. A 3-D model of the entire thickness of the Desert Creek zone likewise displays the same general northwest-southeast trend as do the structural diagrams, with elongate thins and thicks. The 3-D models of the thickness of lower Desert Creek intervals display an elongate, northwest-southeast-trending carbonate buildup depicting the typical, nearshore, shoreline-linear facies tracts of the Desert Creek zone in the northern Blanding sub-basin. The 3-D diagrams of the net feet of log-derived porosity greater than 10 and 12 percent in the lower Desert Creek show an elongate reservoir buildup with two subsidiary thicks separated by a slightly thinner saddle that may represent an intermound trough. Both porosity diagrams show a decrease along the northeast flank of the buildup, which when combined with a coincident high in the top of the lower Desert Creek create a combination stratigraphic/ structural trap.

Reservoir volumes (in acre-feet) were calculated for the Cherokee and Bug fields. Recovery factors of 20 barrels of oil (BO) and 380 thousand cubic feet of gas (MCFG) per acre-foot, respectively, were used for Cherokee field to determine the upper Ismay primary oil and gas recovery. The total volume of Cherokee field porosity units 1 through 5 is 17,522 acre-feet, and may contain over 350,000 BO and 6.6 BCFG (billion cubic feet of gas) primary recovery. Based on these calculations, the remaining recoverable oil and gas reserves at Cherokee field are nearly 168,000 BO and 3 BCFG, suggesting the presence of additional undrained zones (microporosity). Using a price of \$30/bbl and \$4/MCFG, the unrisked value of the remaining recoverable reserves is over \$5 million and \$11 million for oil and gas, respectively.

Recovery factors of 41 BO and 103 MCFG per acre-foot were used for Bug field to determine the lower Desert Creek clean carbonate primary oil and gas recovery. The volume calculated for net feet porosity greater than 10 percent by log analysis is 99,057 acre-feet. This suggests the presence of additional undrained zones (micro-box-work porosity). The lower Desert Creek clean carbonate may contain recoverable oil and gas reserves of nearly 2,440,000 BO and 5.7 BCFG. Again, using prices of \$30/BO and \$4/MCFG, the unrisked value of the remaining reserves is over \$73 million and \$22 million for oil and gas, respectively.

Technology transfer activities for the reporting period consisted of technical presentations to the University of Utah Student Chapter of the American Association of Petroleum Geologists, and to the Rocky Mountain Section of the Society for Sedimentary Geology (SEPM). Cores, regional facies maps, diagenetic analysis, and horizontal drilling recommendations were part of these presentations. The project home page was updated on the Utah Geological Survey Web site. Project team members also published an abstract and semi-annual report detailing project progress and results.

INTRODUCTION

Project Overview

Over 400 million barrels (64 million m^3) of oil have been produced from the shallow-shelf carbonate reservoirs in the Pennsylvanian (Desmoinesian) Paradox Formation in the Paradox Basin, Utah and Colorado (figure 1). With the exception of the giant Greater Aneth field, the other 100-plus oil fields in the basin typically contain 2 to 10 million barrels (0.3-1.6 million m^3) of original oil in place. Most of these fields are characterized by high initial production rates followed by a very short productive life (primary), and hence premature abandonment. Only 15 to 25 percent of the original oil in place is recoverable during primary production from conventional vertical wells.

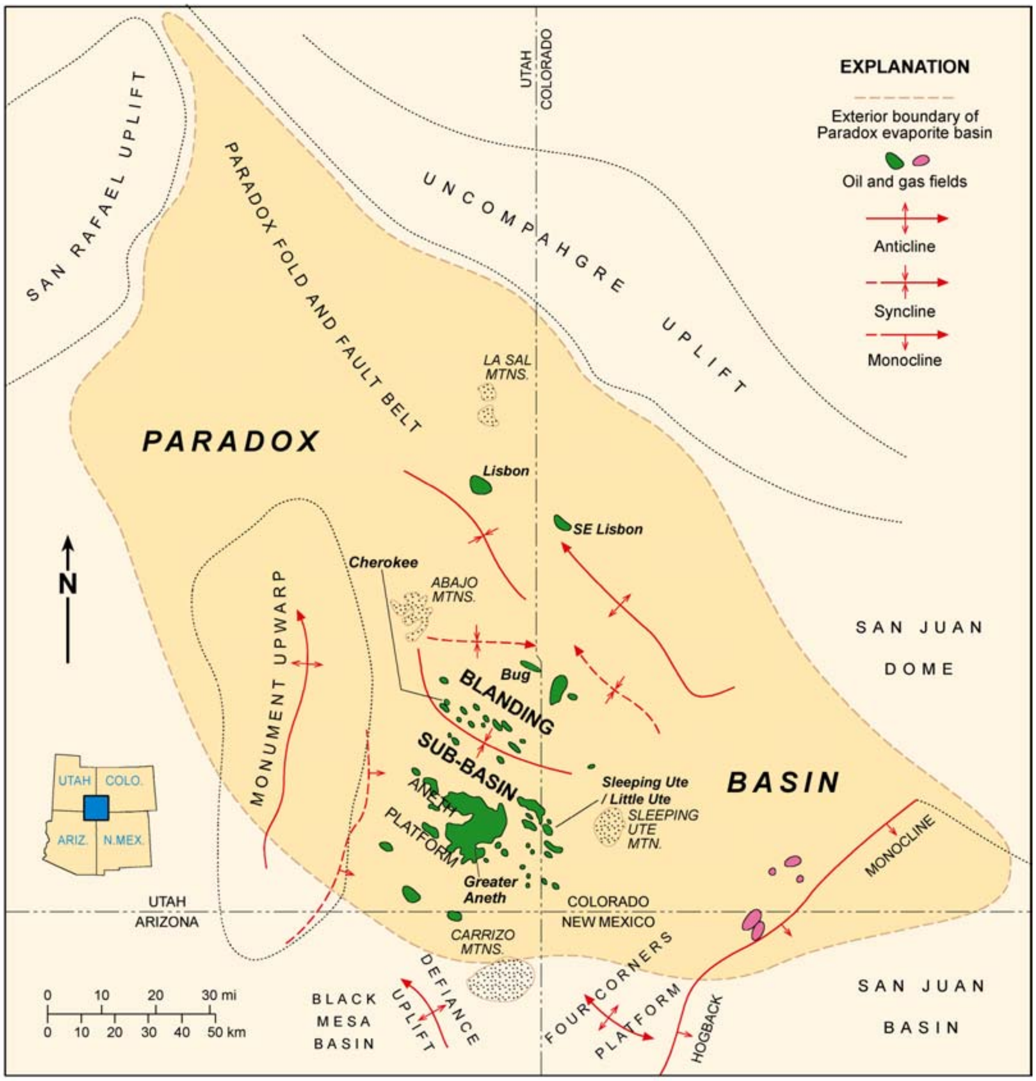


Figure 1. Location map of the Paradox Basin, Utah, Colorado, Arizona, and New Mexico showing producing oil and gas fields, the Paradox fold and fault belt, and Blanding sub-basin as well as surrounding Laramide basins and uplifts (modified from Harr, 1996).

An extensive and successful horizontal drilling program has been conducted in the giant Greater Aneth field. However, to date, only two horizontal wells have been drilled in small Ismay and Desert Creek fields. The results from these wells were disappointing due to the previously poor understanding of the carbonate facies and diagenetic fabrics that create reservoir heterogeneity. These small fields, and similar fields in the basin, are at high risk of premature abandonment. At least 200 million barrels (31.8 million m^3) of oil will be left behind in these small fields because current development practices leave compartments of the heterogeneous reservoirs undrained. Through proper geological evaluation of the reservoirs, production may be increased by 20 to 50 percent through the drilling of low-cost, single, or multilateral horizontal legs from existing vertical development wells. In addition, horizontal drilling from existing wells minimizes surface disturbances and costs for field development, particularly in the environmentally sensitive areas of southeastern Utah and southwestern Colorado.

The Utah Geological Survey (UGS), Colorado Geological Survey (CGS), Eby Petrography & Consulting, Inc., and Seeley Oil Company have entered into a cooperative agreement with the U.S. Department of Energy (DOE) as part of its Class II Oil Revisit Program. A three-phase, multidisciplinary approach is planned to increase production and reserves from the shallow-shelf carbonate reservoirs in the Ismay and Desert Creek zones of the Paradox Basin.

Phase 1 is a geological and reservoir characterization of selected, diversified, small fields, including Cherokee and Bug fields in San Juan County, Utah (figure 1), to identify those field(s) having the greatest potential as targets for increased well productivity and ultimate recovery in a pilot demonstration project. This phase includes: (a) determination of regional geological setting; (b) analysis of the reservoir heterogeneity, quality, lateral continuity, and compartmentalization within the fields; (c) construction of lithologic, microfacies, porosity, permeability, and net pay maps of the fields; (d) determination of field reserves and recovery; and (e) integration of geological data in the design of single or multiple horizontal laterals from existing vertical wells.

Phase 2 is a field demonstration project of the horizontal drilling techniques identified as having the greatest potential for increased field productivity and ultimate recovery. The demonstration project will involve drilling one or more horizontal laterals from the existing, vertical, field well(s) to maximize production from the zones of greatest potential.

Phase 3 includes: (a) reservoir management and production monitoring, (b) economic evaluation of the results, and (c) determination of the ability to transfer project technologies to other similar fields in the Paradox Basin and throughout the U.S.

Phases 1, 2, and 3 will have continuous, but separate, technical transfer activities including: (a) an industry outreach program; (b) a core workshop/seminar in Salt Lake City; (c) publications and technical presentations; (d) a project home page on the Utah Geological Survey and Colorado Geological Survey Web sites; (e) digital databases, maps, and reports; (f) a summary of regulatory, economic, and financial needs; and (g) annual meetings with a Technical Advisory Board and Stake Holders Board.

Project Benefits and Potential Application

The overall benefit of this multi-year project would be enhanced domestic petroleum production by demonstrating and transferring an advanced-oil-recovery technology throughout the small oil fields of the Paradox Basin. Specifically, the benefits expected from the project are: (1) increasing recovery and reserve base by identifying untapped compartments created by reservoir heterogeneity; (2) preventing premature abandonment of numerous small fields; (3) increasing deliverability by horizontally drilling along the reservoir's optimal fluid-flow paths; (4) identifying reservoir trends for field extension drilling and stimulating exploration in Paradox Basin fairways; (5) reducing development costs by more closely delineating minimum field size and other parameters necessary for horizontal drilling; (6) allowing for minimal surface disturbance by drilling from existing, vertical, field well pads; (7) allowing limited energy investment dollars to be used more productively; and (8) increasing royalty income to the federal, state, and local governments, the Ute Mountain Ute Indian Tribe, and fee owners. These benefits may also apply to other areas, including algal-mound and carbonate buildup reservoirs on the eastern and northwestern shelves of the Permian Basin in Texas, Silurian pinnacle and patch reefs of the Michigan and Illinois Basins, and shoaling carbonate island trends of the Williston Basin.

The results of this project are transferred to industry and other researchers through Technical Advisory and Stake Holders Boards, an industry outreach program, digital project databases, and project Web pages. Project results are also disseminated via technical workshops and seminars, field trips, technical presentations at national and regional professional meetings, and papers in various technical or trade journals.

GEOLOGIC SETTING

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado with small portions in northeastern Arizona and the northwestern corner of New Mexico (figure 1). The Paradox Basin is an elongate, northwest-southeast-trending, evaporitic basin that predominately developed during the Pennsylvanian (Desmoinesian), about 330 to 310 million years ago (Ma). During the Pennsylvanian, a pattern of basins and fault-bounded uplifts developed from Utah to Oklahoma as a result of the collision of South America, Africa, and southeastern North America (Kluth and Coney, 1981; Kluth, 1986), or from a smaller-scale collision of a microcontinent with south-central North America (Harry and Mickus, 1998). One result of this tectonic event was the uplift of the Ancestral Rockies in the western United States. The Uncompahgre Highlands in eastern Utah and western Colorado initially formed as the westernmost range of the Ancestral Rockies during this ancient mountain-building period. The Uncompahgre Highlands (uplift) is bounded along the southwestern flank by a large basement-involved, high-angle, reverse fault identified from geophysical seismic surveys and exploration drilling. As the highlands rose, an accompanying depression, or foreland basin, formed to the southwest — the Paradox Basin. Rapid subsidence, particularly during the Pennsylvanian and then continuing into the Permian, accommodated large volumes of evaporitic and marine sediments that intertongue with non-marine arkosic material shed from the highland area to the northeast (Hintze, 1993). The Paradox Basin is surrounded by other uplifts and basins that formed during the Late Cretaceous-early Tertiary Laramide orogeny (figure 1).

The Paradox Basin can generally be divided into two areas: the Paradox fold and fault belt in the north, and the Blanding sub-basin in the south-southwest (figure 1). Most oil production comes from the Blanding sub-basin. The source of the oil is several black, organic-rich shales within the Paradox Formation (Hite and others, 1984; Nuccio and Condon, 1996).

The relatively undeformed Blanding sub-basin developed on a shallow-marine shelf which locally contained algal-mound and other carbonate buildups in a subtropical climate.

The two main producing zones of the Paradox Formation are informally named the Ismay and the Desert Creek (figure 2). The Ismay zone is dominantly limestone, comprising equant buildups of phylloid-algal material with locally variable, small-scale subfacies (figure 3A) and capped by anhydrite. The Ismay produces oil from fields in the southern Blanding sub-basin (figure 4). The Desert Creek zone is dominantly dolomite, comprising regional, nearshore, shoreline trends with highly aligned, linear facies tracts (figure 3B). The Desert Creek produces oil in fields in the central Blanding sub-basin (figure 4). Both the Ismay and Desert Creek buildups generally trend northwest-southeast. Various facies changes and extensive diagenesis have created complex reservoir heterogeneity within these two diverse zones.

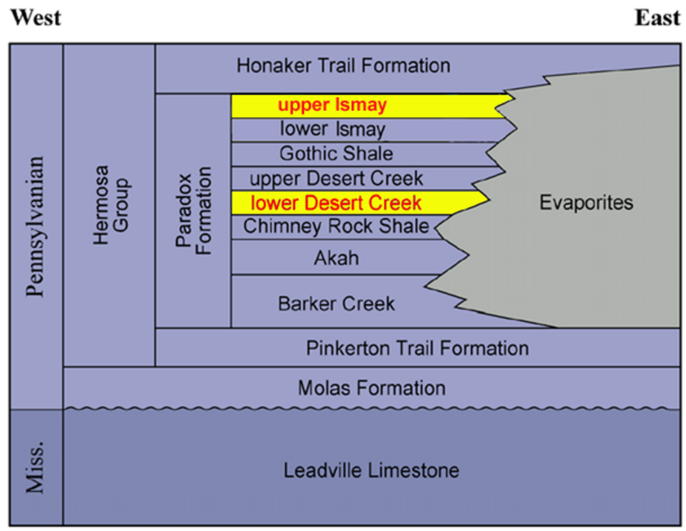


Figure 2. Pennsylvanian stratigraphy of the southern Paradox Basin including informal zones of the Paradox Formation.

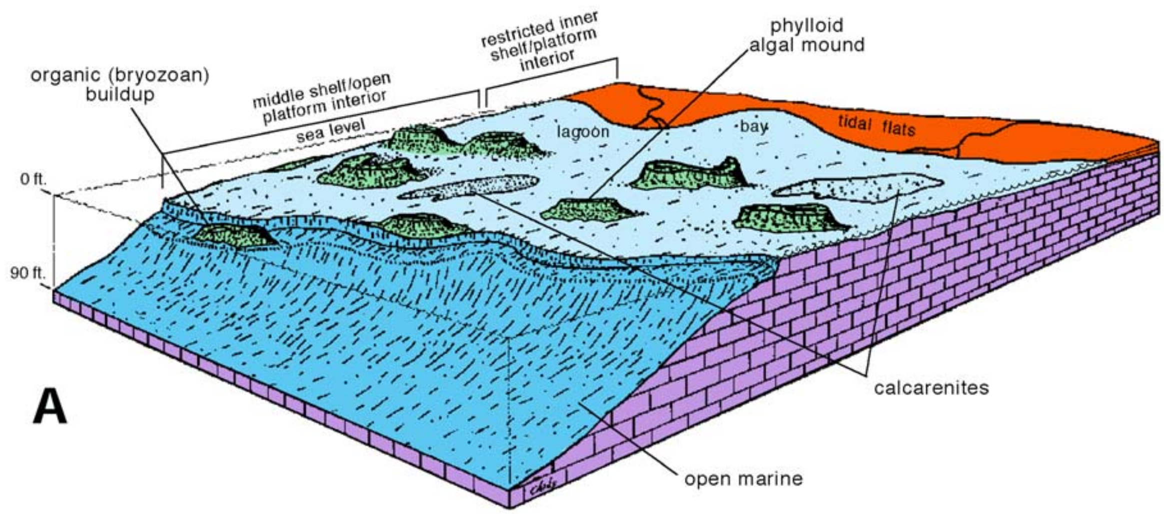
CASE-STUDY FIELDS

Two Utah fields were selected for local-scale evaluation and geological characterization: Cherokee in the Ismay trend and Bug in the Desert Creek trend (figure 4). This evaluation included data collection and reservoir mapping used to create three-dimensional (3-D) models and calculate reserves of these fields, as summarized in this report.

This geological characterization focused on reservoir heterogeneity, quality, and lateral continuity, as well as possible compartmentalization within the fields. From these evaluations, untested or under-produced compartments are being identified as targets for horizontal drilling. The models resulting from the geological and reservoir characterization of these fields can be applied to similar fields in the basin (and other basins as well) where data might be limited.

Cherokee Field

Cherokee field (figure 4) is a phylloid-algal buildup capped by anhydrite that produces from porous algal limestone and dolomite in the upper Ismay zone. The net reservoir thickness is 27 feet (8.2 m), which extends over a 320-acre (130 ha) area. Porosity averages 12 percent with 8 millidarcies (mD) of permeability in vuggy and intercrystalline pore systems. Water saturation is 38.1 percent (Crawley-Stewart and Riley, 1993).



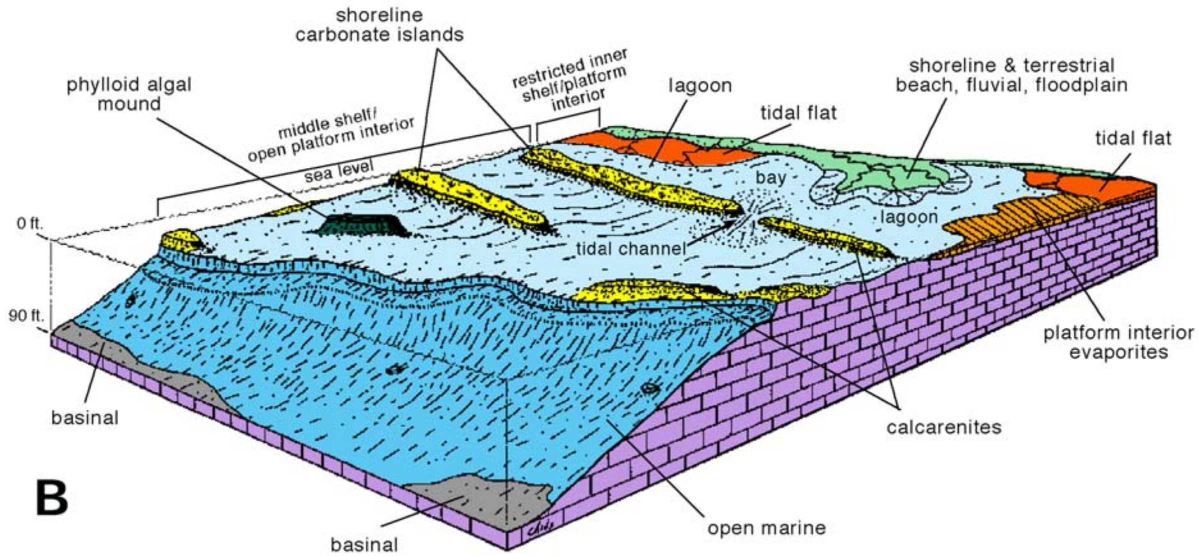


Figure 3. Block diagrams displaying major depositional facies, as determined from core, for the Ismay (A) and Desert Creek (B) zones, Pennsylvanian Paradox Formation, Utah and Colorado.

Cherokee field was discovered in 1987 with the completion of the Meridian Oil Company Cherokee Federal 11-14, NE1/4NW1/4 section 14, T. 37 S., R. 23 E., Salt Lake Base Line and Meridian (SLBL&M); initial flowing potential (IFP) was 53 barrels of oil per day (BOPD) (8.4 m^3), 990 thousand cubic feet of gas per day (MCFGPD) (28 MCMPD), and 26 barrels of water (4.1 m^3). There are currently four producing (or shut-in) wells and two dry holes in the field. The well spacing is 80 acres (32 ha). The present field reservoir pressure is estimated at 150 pounds per square inch (psi) (1,034 kPa). Cumulative production as of January 1, 2004, was 182,464 barrels of oil (29,012 m^3), 3.67 billion cubic feet of gas (BCFG) (0.1 BCMG), and 3,358 barrels of water (534 m^3) (Utah Division of Oil, Gas and Mining, 2003). The original estimated primary recovery is 172,000 barrels of oil (27,348 m^3) and 3.28 BCFG (0.09 BCMG) (Crawley-Stewart and Riley, 1993). The fact that both these estimates have been surpassed suggests significant additional reserves could remain.

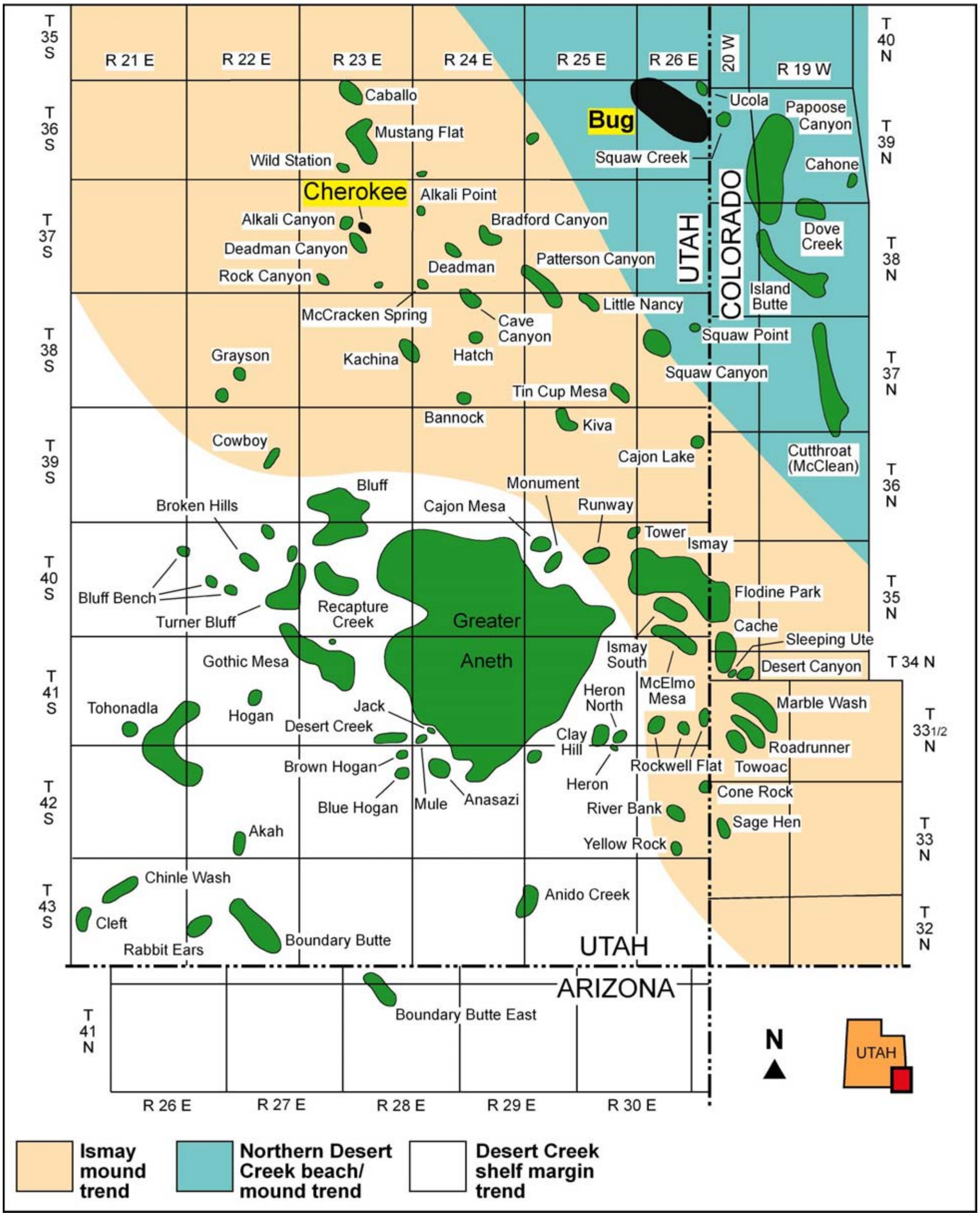


Figure 4. Project study area and fields (case-study fields in black) within the Ismay and Desert Creek producing trends in the Blanding sub-basin, Utah and Colorado.

Bug Field

Bug field (figure 4) is an elongate, northwest-trending, carbonate buildup in the lower Desert Creek zone. The producing units vary from porous dolomitized bafflestone to packstone and wackestone. The trapping mechanism is an updip porosity pinchout. The net reservoir thickness is 15 feet (4.6 m) over a 2,600-acre (1,052 ha) area. Porosity averages 11 percent in moldic, vuggy, and intercrystalline networks. Permeability averages 25 to 30 mD, but ranges from less than 1 to 500 mD. Water saturation is 32 percent (Martin, 1983; Oline, 1996).

Bug field was discovered in 1980 with the completion of the Wexpro Bug No. 1, NE1/4SE1/4 section 12, T. 36 S., R. 25 E., SLBL&M, for an IFP of 608 BOPD (96.7 m^3), 1,128 MCFGPD (32 MCMPD), and 180 barrels of water (28.6 m^3). There are currently eight producing (or shut-in) wells, five abandoned producers, and two dry holes in the field. The well spacing is 160 acres (65 ha). The present reservoir field pressure is 3,550 psi (24,477 kPa). Cumulative production as of January 1, 2004, was 1,622,455 barrels of oil (257,970 m^3), 4.48 BCFG (0.13 BCMG), and 3,181,467 barrels of water (505,850 m^3) (Utah Division of Oil, Gas and Mining, 2003). Estimated primary recovery is 1,600,000 bbls (254,400 m^3) of oil and 4 BCFG (0.1 BCMG) (Oline, 1996). Again, since the original reserve estimates have been surpassed and the field is still producing, significant additional reserves likely remain.

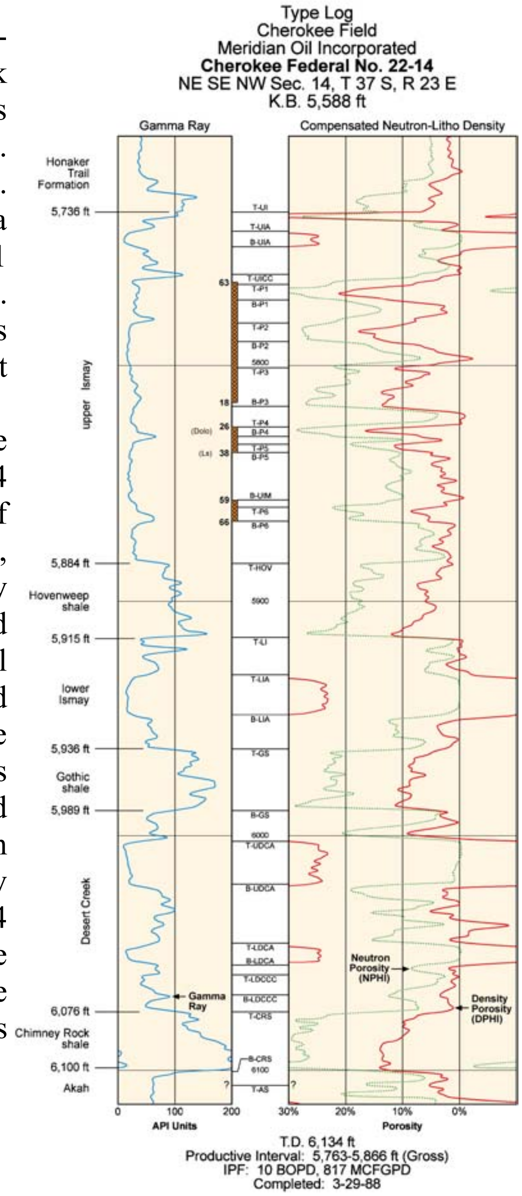


Figure 5. Type log for the Cherokee field (gamma-ray, compensated neutron-litho density) from the Cherokee Federal No. 22-14 well, showing the Ismay and Desert Creek correlation scheme, major units, and productive intervals (refer to table 1 for explanation of unit abbreviations).

CORRELATION SCHEME USED IN MAPPING

The structure and isochore maps used to generate 3-D models employed a correlation scheme developed early in the project. This correlation scheme tied the core-derived, typical, vertical sequence or cycle of depositional facies from the Cherokee and Bug case-study fields to the corresponding gamma-ray and neutron-density curves from geophysical well logs. The correlation scheme identified major zone contacts, seals or barriers, baffles, producing or potential reservoirs, and depositional facies (figures 5 through 7, and table 1).

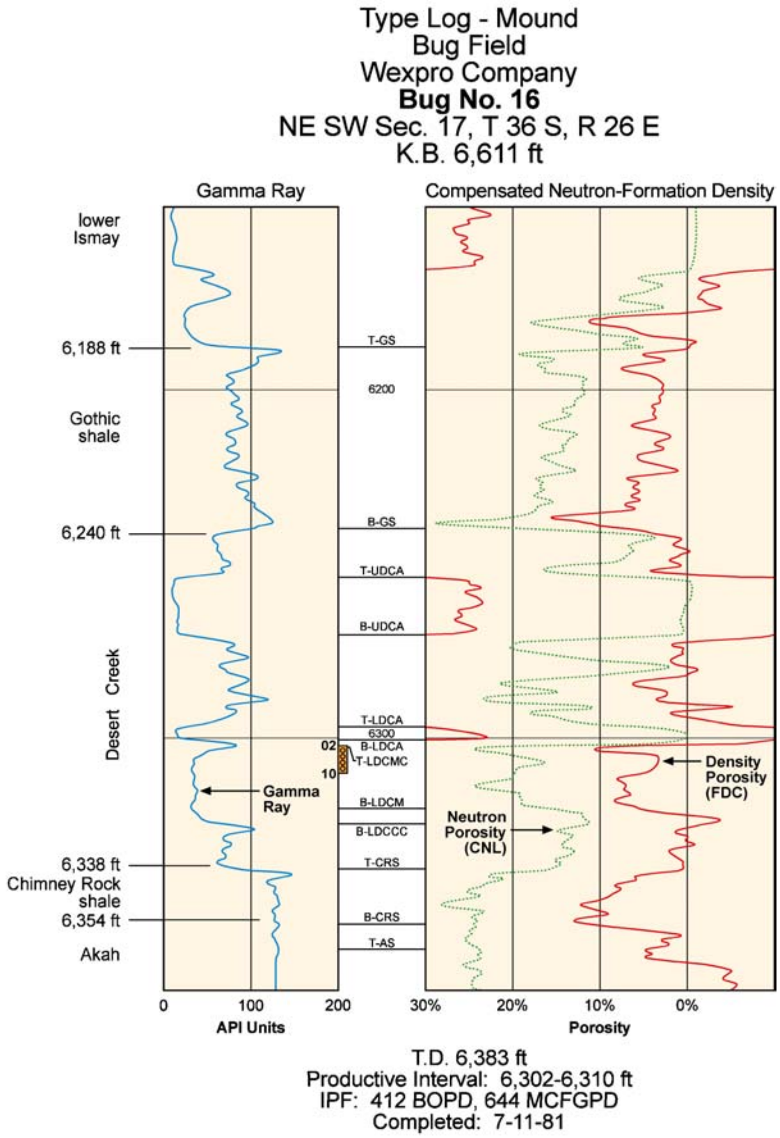


Figure 6. Type log for the Bug field mound (gamma-ray, compensated neutron-formation density) from the Bug No. 16 well, showing the Desert Creek correlation scheme, major units, and productive interval (refer to table 1 for explanation of unit abbreviations).

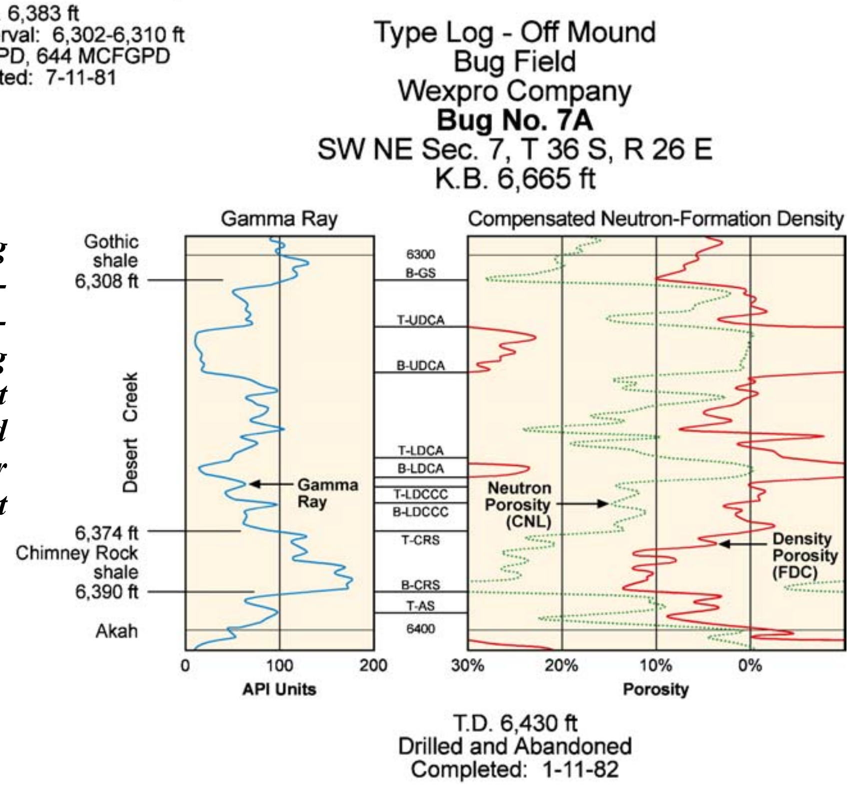


Figure 7. Type log for the Bug field off-mound area (gamma-ray, compensated neutron-formation density) from the Bug No. 7A well, showing the Desert Creek correlation scheme and major units (refer to table 1 for explanation of unit abbreviations).

Table 1. Correlation scheme used for Ismay and Desert Creek zones of the Paradox Formation in Cherokee and Bug fields, Blanding sub-basin, Utah.

Unit Code	Description
T-UI	Top – upper Ismay zone
T-UIA	Top – upper Ismay anhydrite
B-UIA	Base - upper Ismay anhydrite
T-UIA2	Top – upper Ismay anhydrite 2
B-UIA2	Base – upper Ismay anhydrite 2
T-UICC	Top – upper Ismay clean carbonate
T-P1	Top – porosity unit #1
B-P1	Base – porosity unit #1
T-P2	Top – porosity unit #2
B-P2	Base – porosity unit #2
T-P3	Top – porosity unit #3
B-P3	Base – porosity unit #3
T-P4	Top – porosity unit #4
B-P4	Base – porosity unit #4
T-P5	Top – porosity unit #5
B-P5	Base – porosity unit #5
B-UIM	Base – upper Ismay mound
B-UICC	Base upper Ismay clean carbonate
T-P6	Top – porosity unit #6
B-P6	Base – porosity unit #6
T-HOV	Top – Hovenweap shale
T-LI	Top – lower Ismay zone
T-LIA	Top – lower Ismay anhydrite
B-LIA	Base – lower Ismay anhydrite
T-GS	Top – Gothic shale
B-GS	Base – Gothic shale
T-UDCA	Top – upper Desert Creek anhydrite
B-UDCA	Base – upper Desert Creek anhydrite
T-LDCA	Top – lower Desert Creek anhydrite
B-LDCA	Base – lower Desert Creek anhydrite
T-LDCMC	Top – lower Desert Creek mound cap
B-LDCM	Base – lower Desert Creek mound

Depositionally, rock units are divided into seals or barriers (anhydrites and shales), mound (carbonate buildup [bafflestone, bindstone, grainstone, and packstone]), and off mound (mudstone and wackestone). Porosity units, and reservoir or potential reservoir layers, are identified within the mound and off-mound intervals. The mound, and some of the off-mound units, are part of the "clean carbonate" packages - intervals containing all of the productive reservoir facies, and where carbonate mudstone and shale are generally absent. The clean carbonate packages abruptly change laterally into thick anhydrite packages, particularly in the upper Ismay zone.

The top and base of all these intervals (seals, mound, clean carbonate, as well as porosity units) were determined and coded as listed on table 1. The unlisted intervening units represent the baffles or non-reservoir rocks, such as non-porous packestone or wackestone (figures 5 through 7). The mound/mound cap intervals usually have porosity greater than 6 percent, while the clean carbonate intervals are defined by lithology only (such as bafflestone or grainstone), although there may be occasional isolated porosity zones. The top and base of the mound/mound cap intervals are often equivalent to the top and base of the clean carbonate intervals. In addition, the top and base of the mound/mound cap intervals may be equivalent to the top and base of the thinner off-mound clean carbonate intervals.

THREE-DIMENSIONAL MODELING – RESULTS AND DISCUSSION

Methods

The 3-D models were created in Environmental Systems Research Institute, Inc. (ESRI) ArcView® 3D Analyst. Structure, isochore, and other reservoir property contour maps (see Deliverable 1.41 and 1.4.2 – Cross Sections and Field Maps: Cherokee and Bug Fields, San Juan County, Utah) were digitized using AutoCad®, then brought into ArcView®. These AutoCad® files were first converted to shape files and then to grids. Next, Triangulated Irregular Network (TIN) files were created. A TIN is an object used to represent a surface. It partitions a surface into a set of contiguous, non-overlapping triangles. Attribute and geometry information was stored for the points, lines, and faces that comprise each triangle. This information was used for display, query, and analysis purposes. A height value was recorded for each triangle node. Heights between nodes were interpolated, thus allowing for the definition of a continuous surface. TINs can accommodate irregularly distributed, as well as selective data sets. This made it possible to represent a complex and irregular surface with a small data set (ESRI, 1998).

The TIN was imported into a 3D Analyst scene (called a viewer) and a projection was set selected from a specific projection or coordinate system from one of the following categories: Projections of the World, Projections of a Hemisphere, Projections of the United States, State Plane – 1927, State Plane – 1983, Universal Transverse Mercator (UTM), or National Grids. Once the map projections or coordinate system categories have been selected, ArcView® displays the parameters that it uses in the projection, such as the Ellipsoid, Central Meridian, Reference Latitude and Standard Parallels. If no projection is set, TIN themes are displayed using the coordinates found in their data set. Also brought into the scene was a feature theme for the wells created from UTM coordinates. Each well has a set of coordinates. Feature themes and TIN themes had to be in the same coordinate system to display them together without a projection. To set a projection, feature themes had to be in decimal degrees and TIN themes had to be in the projection set for them (ESRI, 1998).

The scene's 3-D properties were set to control certain aspects of scene display such as sun azimuth (the compass direction of the sun), sun altitude (the height of the sun), and a vertical exaggeration factor. The vertical exaggeration factor is a multiplier used to increase or decrease the vertical dimension of data displayed in the scene's 3-D viewer (ESRI, 1998).

After the viewer scene was projected, each theme property was set. Setting the theme properties allowed us to define height, extrusion, shading, navigation simplification, and transparency properties individually. Each TIN theme had its own legend display in the view's Table of Contents. A TIN theme's legend specified what triangle points, lines, or faces were drawn and what colors were used to draw them. This controlled how the TIN theme was displayed in the view (ESRI, 1998).

The scene was shifted, rotated, panned, or zoomed to any angle without disturbing the way each theme was lined up. After all the angles were set for best viewing position, they were exported as a joint photographic expert group (.jpg) or bitmap (.bmp) image file. This image file was used to create a layout. A layout is a map used to display views and is used to prepare graphics for output from ArcView® (ESRI, 1998). Layouts were printed and exported to a number of formats. The annotations (labels, descriptions, titles, and so forth) were added at this time.

Modeling Interpretation

Cherokee Field

The relative locations of Cherokee field wells used to produce reservoir structure and isochore maps are shown on figure 8. The 3-D diagrams with structural contours on top of the upper and lower Ismay zone (figure 9), the upper Ismay clean carbonate (figure 10), and the Gothic shale (figure 11A) show the same general southwest-dipping structural nose upon which the carbonate buildup developed. This structure ends abruptly suggesting the possible presence of a northwest-southeast-trending normal fault. Intense, late-stage microporosity development along hydrothermal solution fronts in the reservoir rock likely migrated from nearby, unknown fracture and fault zones (see Deliverable 1.2.1A – Thin Section Descriptions: Cherokee and Bug Fields, San Juan County, Utah).

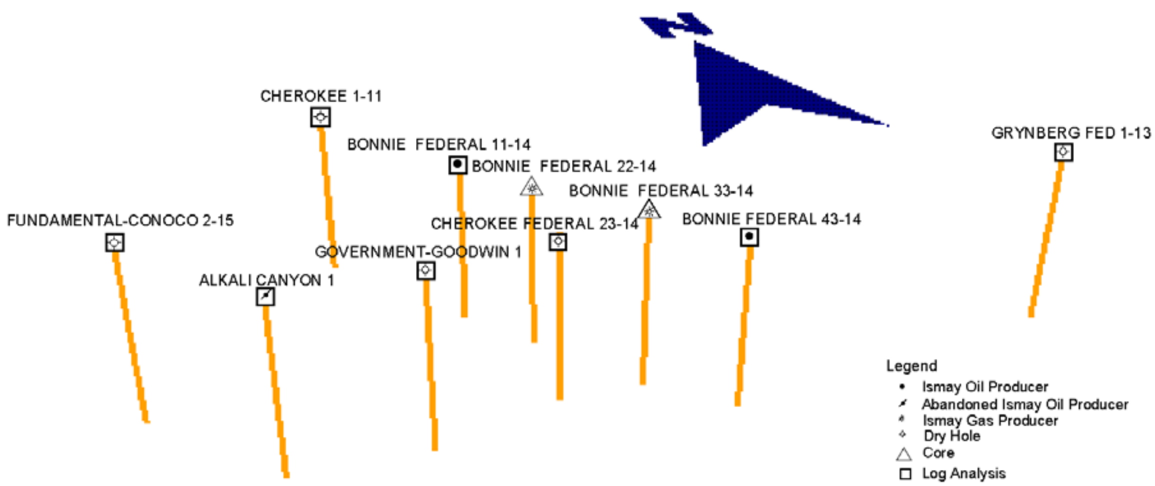


Figure 8. Relative locations and names of wells in the Cherokee field area, San Juan County, Utah.

The 3-D models of the thickness of the Gothic (figure 11B) and Hovenweap (figure 12) shales show a general west-northwest to east-southeast linear trend. Cherokee wells align along a subtle Gothic thickness increase (figure 11B), whereas the carbonate buildup may have developed on a better-defined thick in the shallower Hovenweap (figure 12).

There are two anhydrite units (1 and 2) in the upper Ismay zone (figure 13). They display a similar west-northwest to east-southeast linear trend as the Hovenweap and Gothic shales. Cherokee wells are located in the thickest part of the relatively thin upper Ismay anhydrite 1 (figure 13A). The upper Ismay anhydrite 2 varies in thickness from 80 feet (24 m) to 0 across the map area. This unit is 0 to 15 feet (0-5 m) thick in Cherokee wells, which lie along the edge of thick anhydrite, as seen in both isochore and inverted isochore diagrams (figures 13B and 13C). This situation is similar to the regional upper Ismay facies pattern where intrashelf basins are the locations of thick anhydrite accumulations. Phylloid-algal buildups developed on innershelf and tidal flats within curvilinear bands that rim the intrashelf basins (Eby and others, 2003a, 2003b).

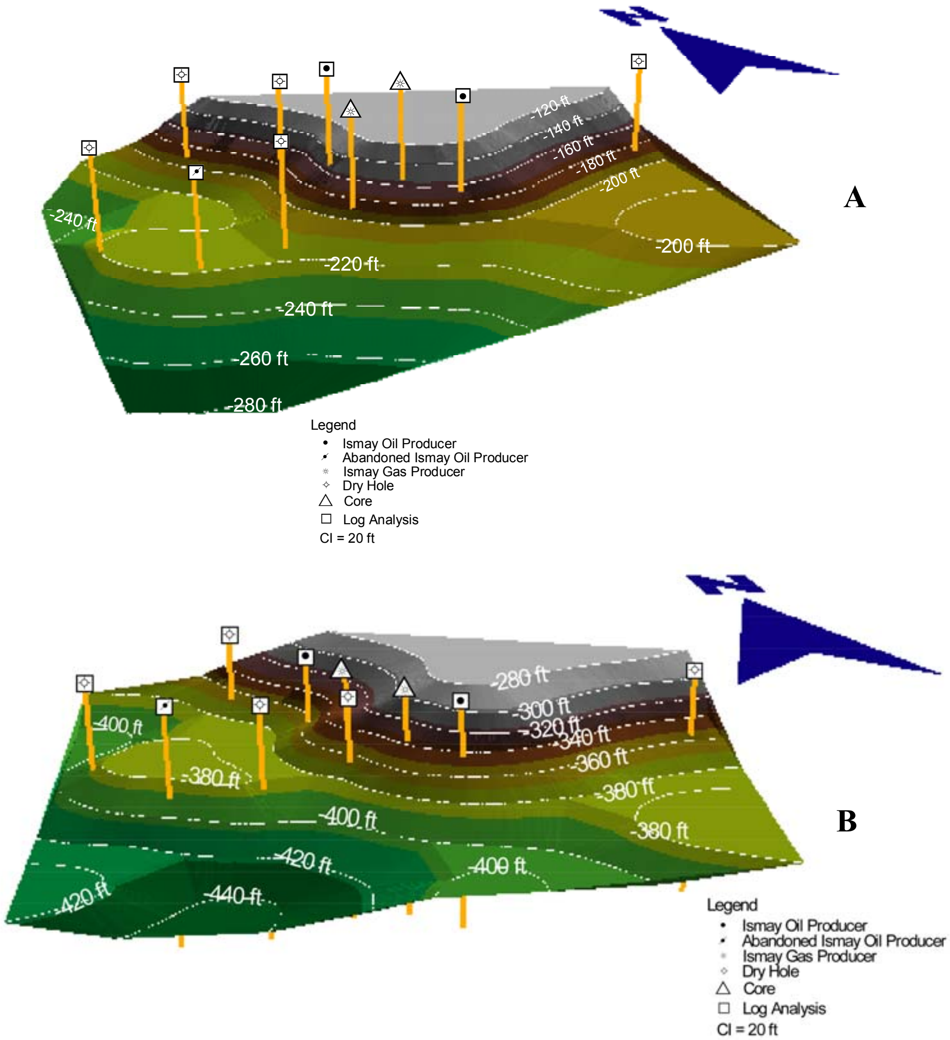


Figure 9. Three-dimensional models, Cherokee field, San Juan County, Utah. (A) Structure contours on top of upper Ismay zone. (B) Structure contours on top of lower Ismay zone.

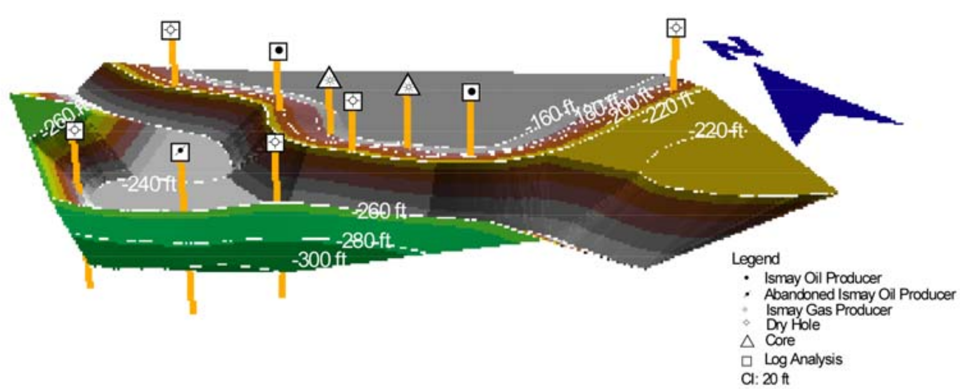


Figure 10. Three-dimensional model with structure contours on top of upper Ismay zone clean carbonate, Cherokee field, San Juan County, Utah.

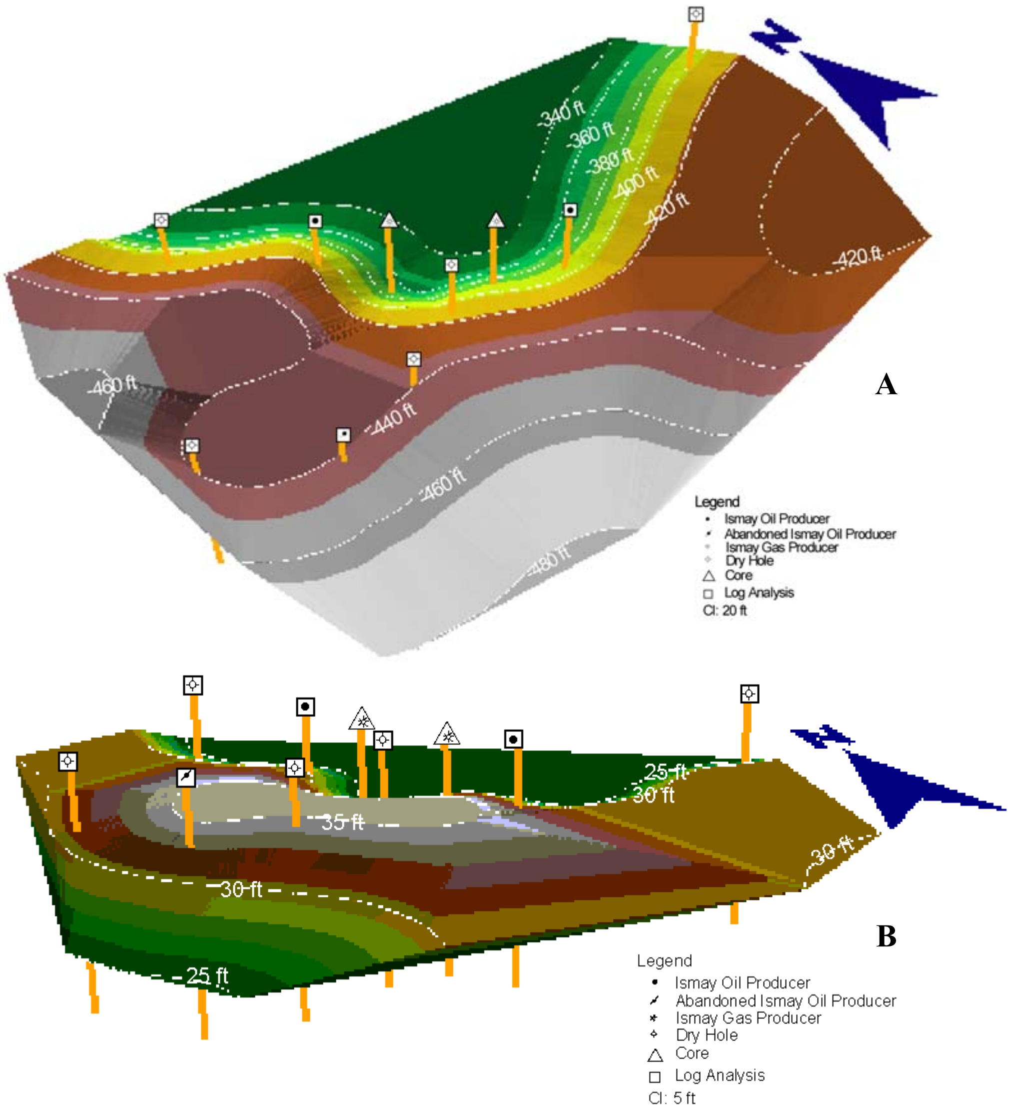


Figure 11. Three-dimensional models, Cherokee field, San Juan County, Utah. (A) Structure contours on top of Gothic shale. (B) Isochore of Gothic shale.

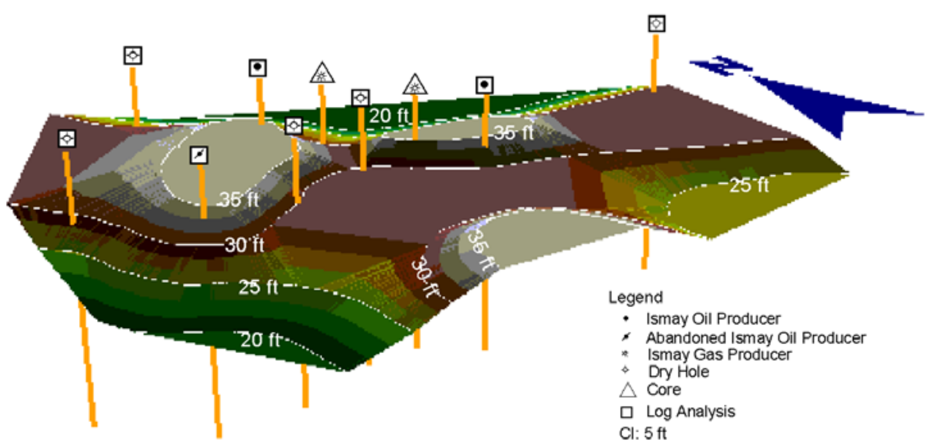


Figure 12. Three-dimensional model of the isochore of the Hovenweap shale, Ismay zone, Cherokee field, San Juan County, Utah.

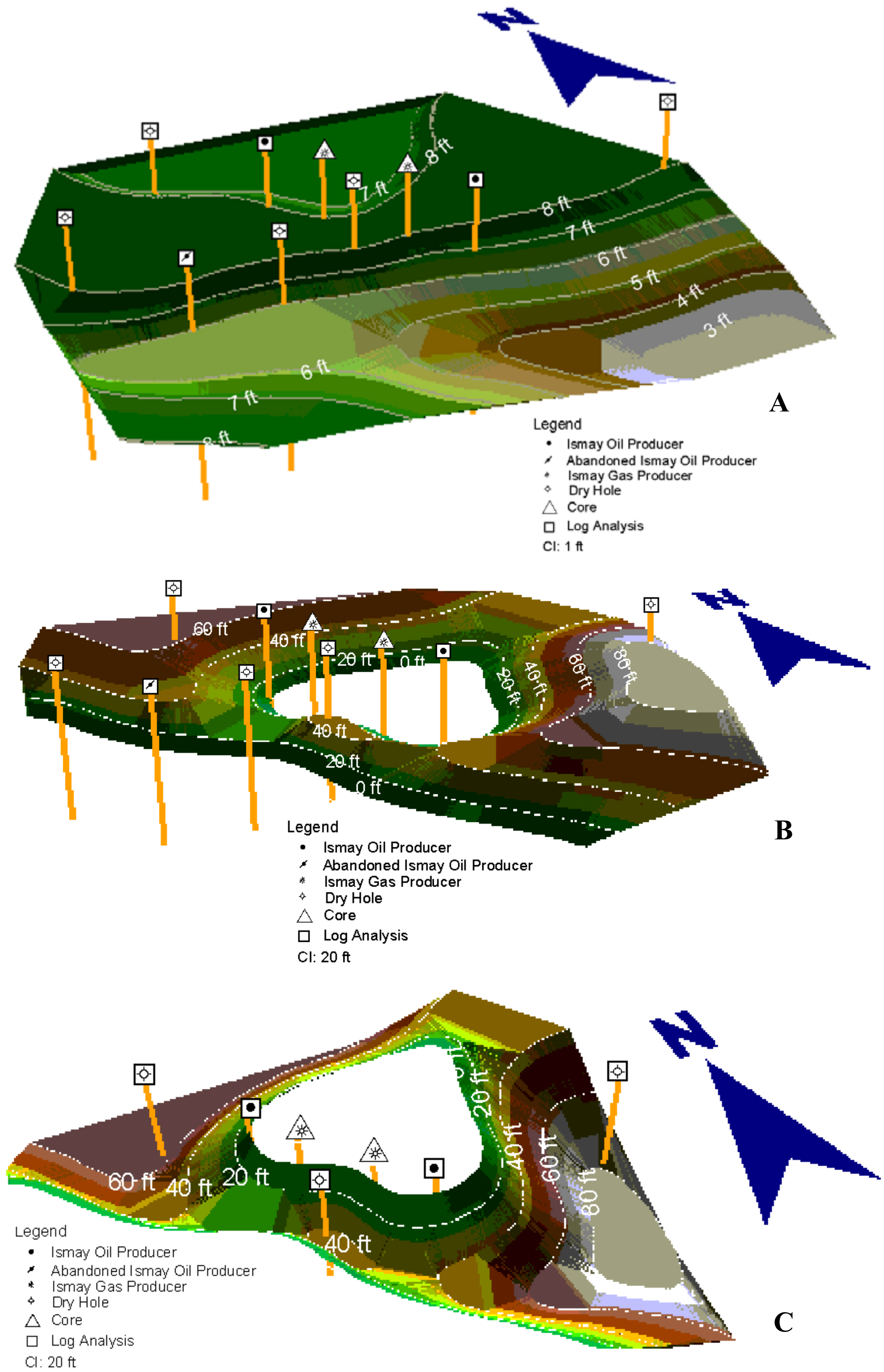


Figure 13. Three-dimensional models, Cherokee field, San Juan County, Utah. (A) Upper Ismay zone anhydrite isochore 1. (B) Upper Ismay zone anhydrite 2 isochore. (C) Upper Ismay zone anhydrite 2 inverted isochore.

Three-dimensional models of the thickness of the entire Ismay zone (figure 14A), upper Ismay (figure 14B), lower Ismay (figure 14C), and upper Ismay clean carbonate (figure 15) also display the same general west-northwest to east-southeast trend punctuated by elongate to slightly equant thicks. Cherokee field is located near thicks shown on Ismay and upper Ismay 3-D diagrams. Surprisingly, the field is located adjacent to the thickest part of the upper Ismay clean carbonate (100 feet [30 m]), although the range from that thick to the thinnest section in Cherokee wells is only 19 feet (6 m).

Five reservoir porosity units (figure 16 through 19), all having porosity greater than 6 percent, are present in the upper Ismay mound, separated by low-porosity/permeability barriers (mudstone and wackestone). These porosity units represent the phylloid-algal buildups composed primarily of bafflestone and grainstone that produce oil and gas in the field. Typical of the upper Ismay trend in the Blanding sub-basin, these units are viewed in 3-D as small, equant-shaped pods. The overall carbonate reservoir for Cherokee field is shown in a combined 3-D diagram on figure 18B, but in reality, the individual porosity units are stacked vertically, displayed diagramatically on figure 19. Porosity unit 5 (figure 18A) is the largest and most likely the major production contributor, as well as holding the bulk of the remaining reserves. The 3-D thickness diagrams suggest all five porosity units have an untested northeastern area.

As expected, 3-D diagrams of the upper Ismay zone depicting net feet of porosity greater than 10 and 12 percent by log analysis (figure 20) show the same equant-shaped buildups as displayed by porosity units 1 through 5. At 12 percent porosity, the diagram shows a thickness pattern which is a slightly smaller match compared to the combined thickness of porosity units 1 through 5 (figure 18B).

Upper Ismay zone net-feet of limestone (figure 21A) and dolomite (figure 21B) were determined by log analysis. The extent of the 3-D diagrams is limited due to the lack of neutron/density logs from older wells in the area. Characteristic of the Ismay zone in the Blanding sub-basin, limestone is the dominant lithology. However, there is an unusual amount of dolomite present. The 3-D thickness diagrams show a large buildup of limestone adjacent to (figure 21A), and dolomite within (figure 21B), Cherokee field. In both cases, a carbonate buildup continues northeast of the field wells.

Bug Field

The relative locations of Bug field wells used to produce reservoir structure and isochore maps are shown on figure 22. The 3-D diagram with structural contours on top of the Gothic shale (figure 23A) shows a general regional dip to the southwest and a subtle, elongate, northwest-southeast-trending anticline. The 3-D model of the thickness of the Gothic shale (figure 23B) shows a similar northwest-southeast trend. Bug wells align along, or adjacent to, a subtle Gothic thickness increase.

The 3-D diagrams with structural contours on top of the Desert Creek zone (figure 24A), lower Desert Creek mound (figure 24B), lower Desert Creek clean carbonate (figure 24A), and Chimney Rock shale (figure 24D) also each show a southwest regional dip. The top of the Desert Creek zone, which is just slightly deeper than the Gothic shale, displays the same subtle, elongate, northwest-southeast-trending anticline. The anticline broadens in the lower Desert Creek mound and clean carbonate, likely representing the buildup itself. At the Chimney Rock shale top, the anticline may depict the topographic high upon which the Bug carbonate buildup developed.

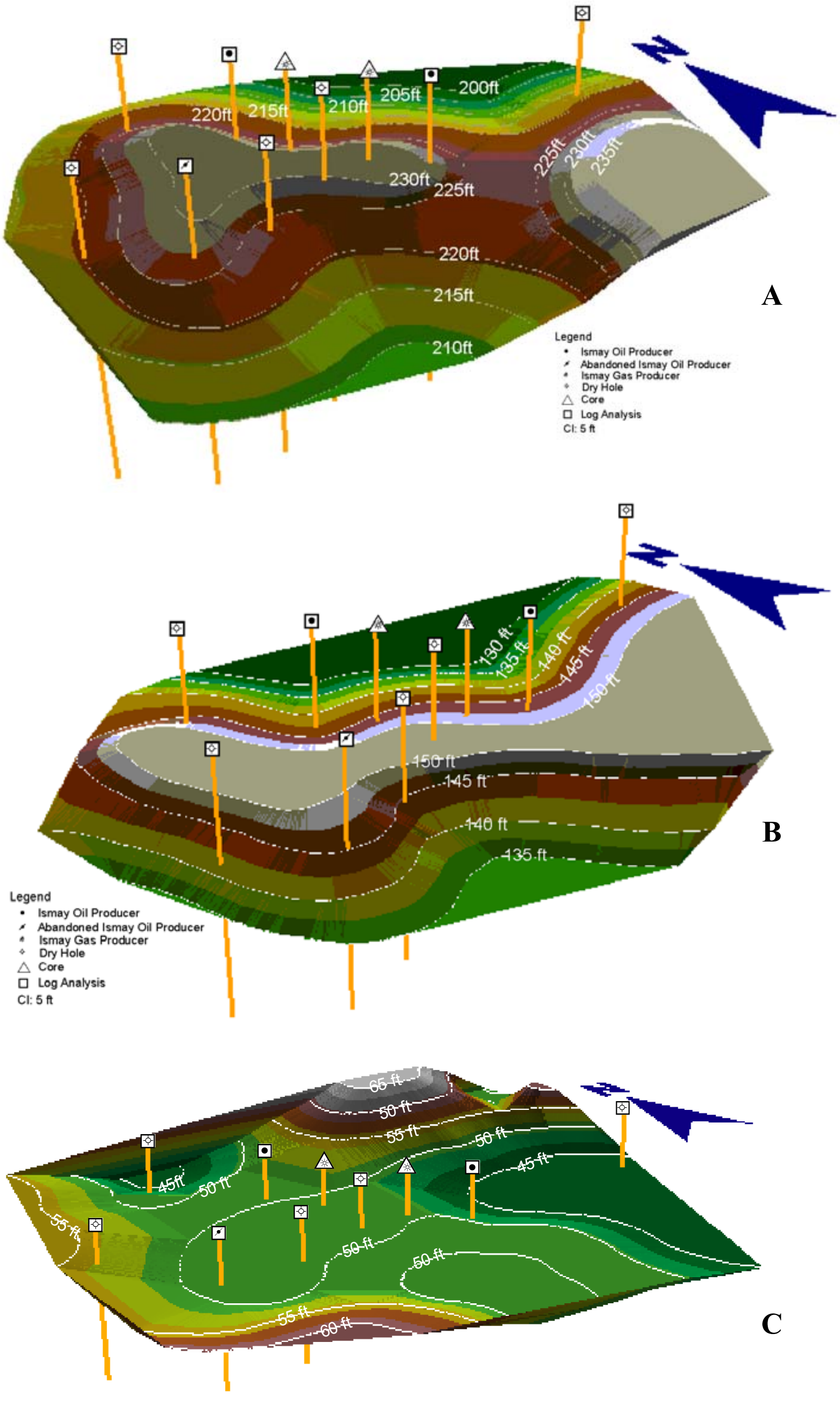


Figure 14. Three-dimensional models, Cherokee field, San Juan County, Utah. (A) Ismay zone isochore. (B) Upper Ismay zone isochore. (C) Lower Ismay zone isochore.

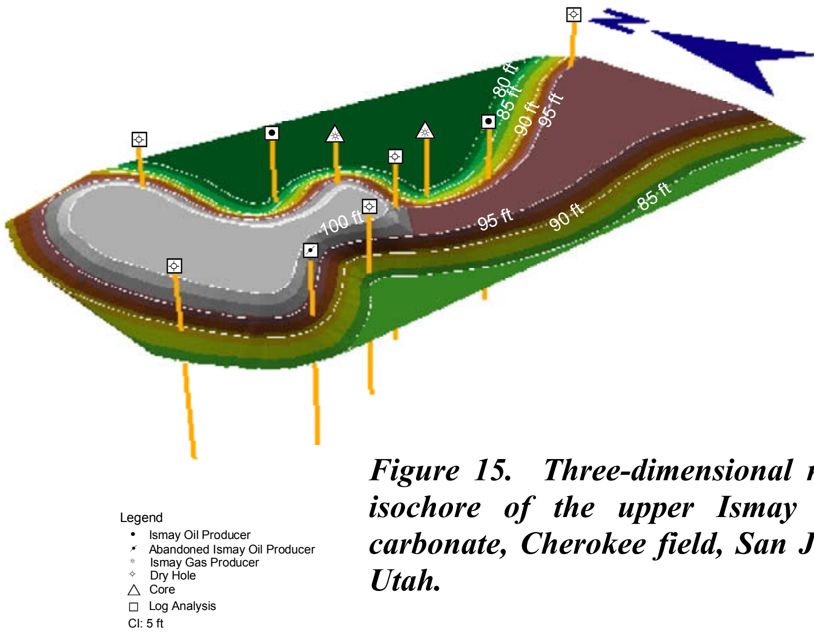


Figure 15. Three-dimensional model of the isochore of the upper Ismay zone, clean carbonate, Cherokee field, San Juan County, Utah.

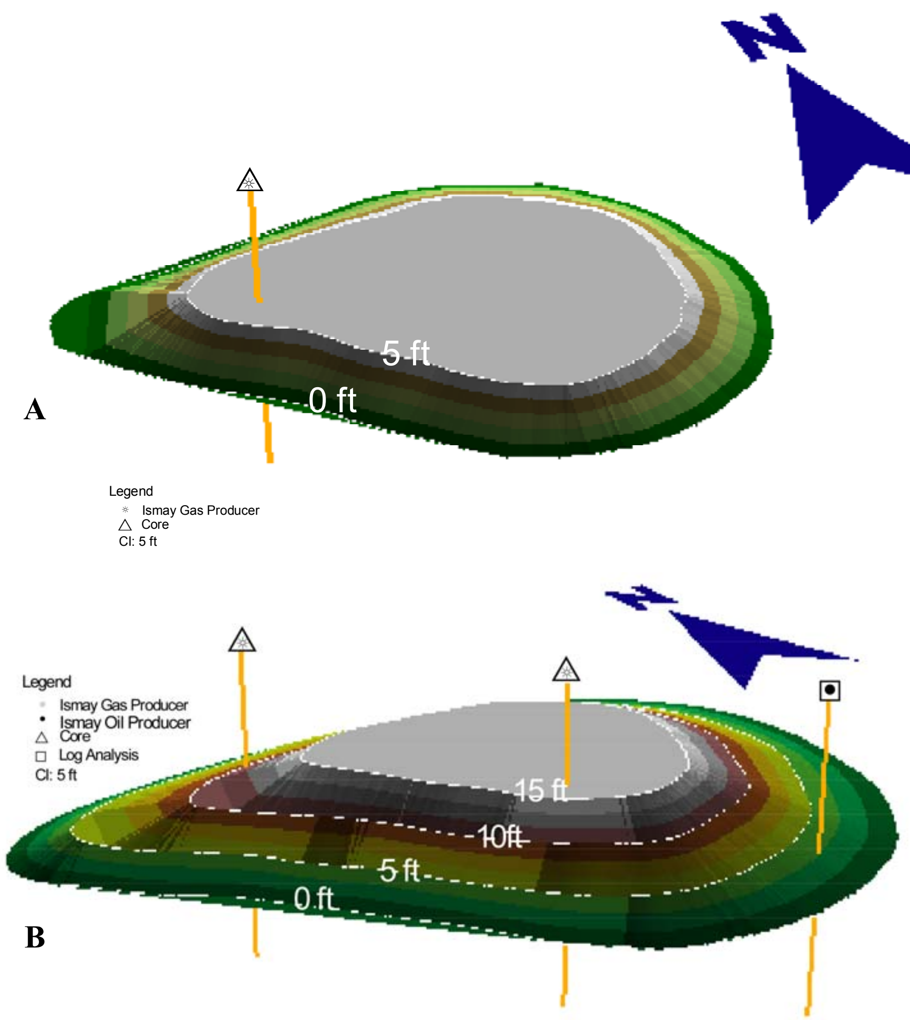


Figure 16. Three-dimensional models, upper Ismay zone, Cherokee field, San Juan County, Utah. (A) Isochore of porosity unit 1. (B) Isochore of porosity unit 2.

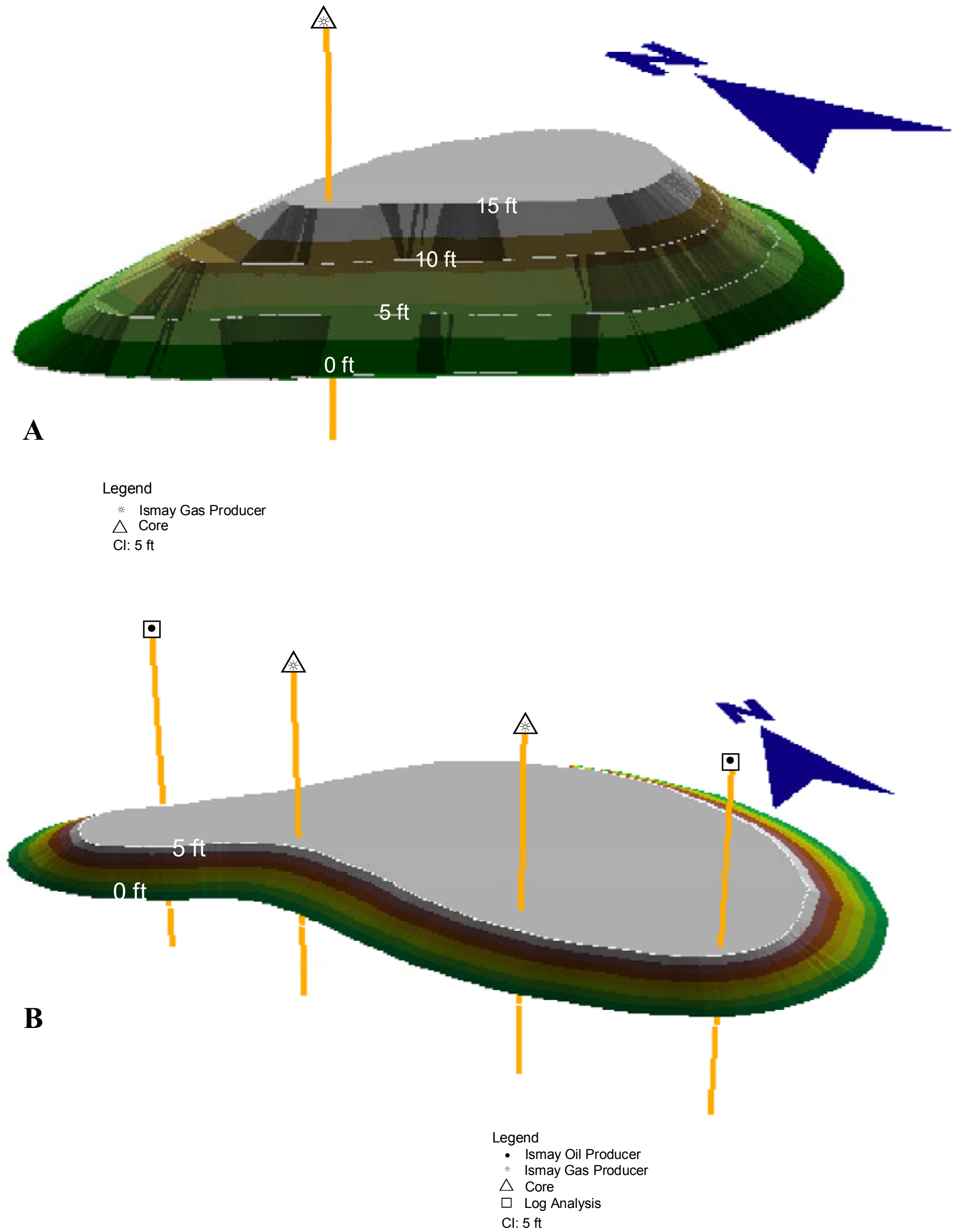


Figure 17. Three-dimensional models, upper Ismay zone, Cherokee field, San Juan County, Utah. (A) Isochore of porosity unit 3. (B) Isochore of porosity unit 4.

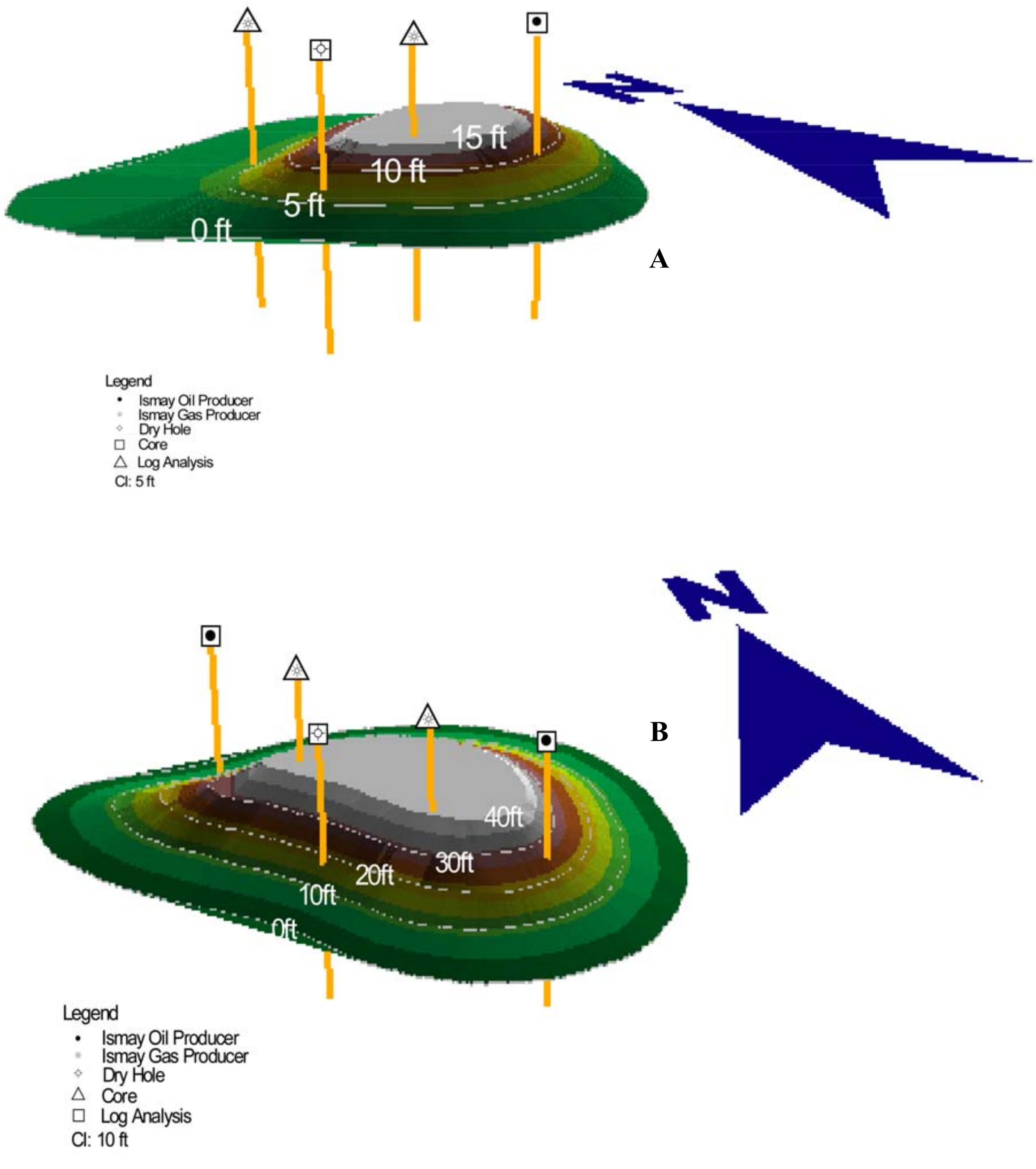


Figure 18. Three-dimensional models, upper Ismay zone, Cherokee field, San Juan County, Utah. (A) Isochore of porosity unit 5. (B) Isochore of porosity units 1 through 5 combined thickness.

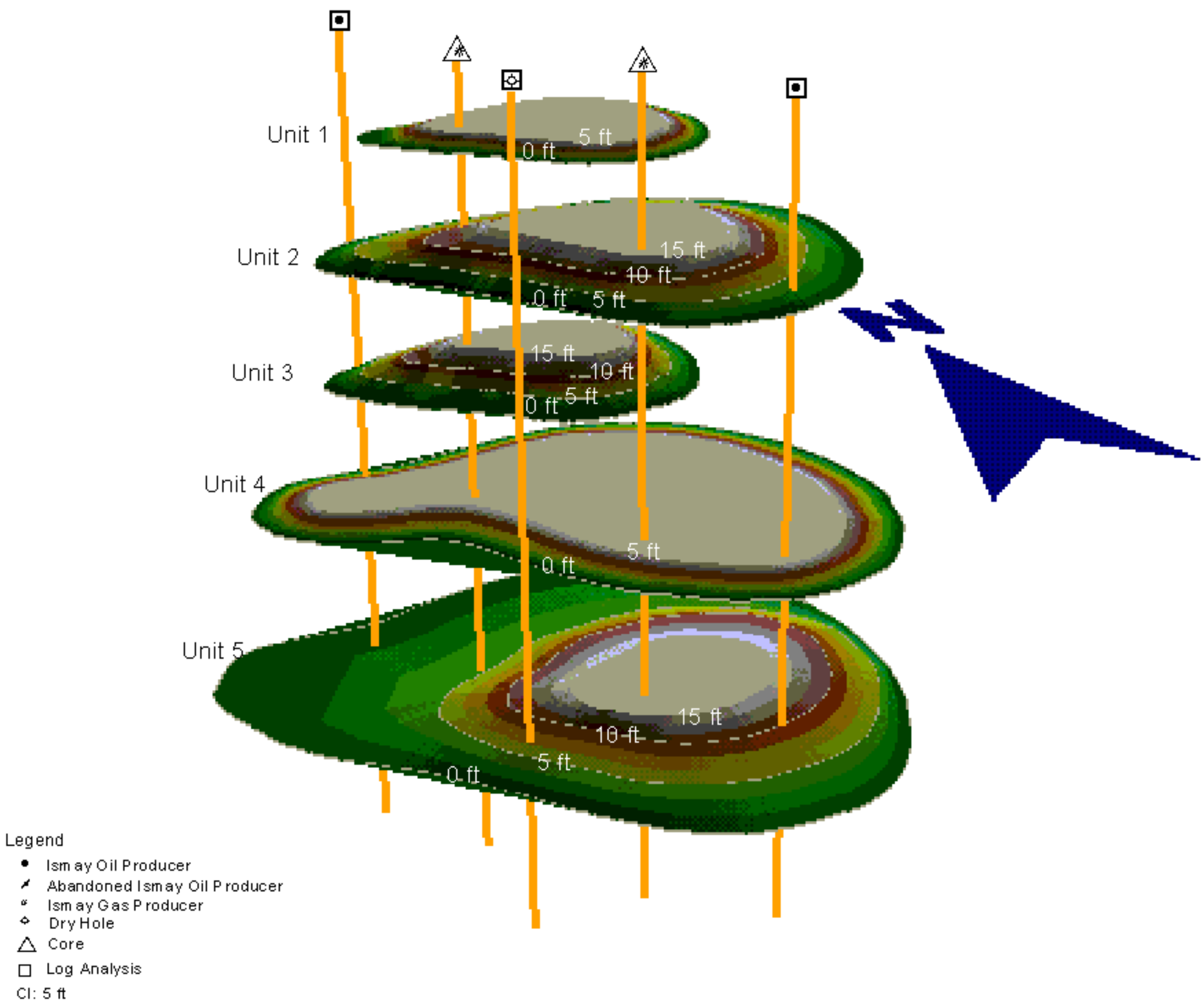


Figure 19. Three-dimensional model of porosity units 1 through 5 isochores vertically stacked (no vertical scale), upper Ismay zone, Cherokee field, San Juan County, Utah.

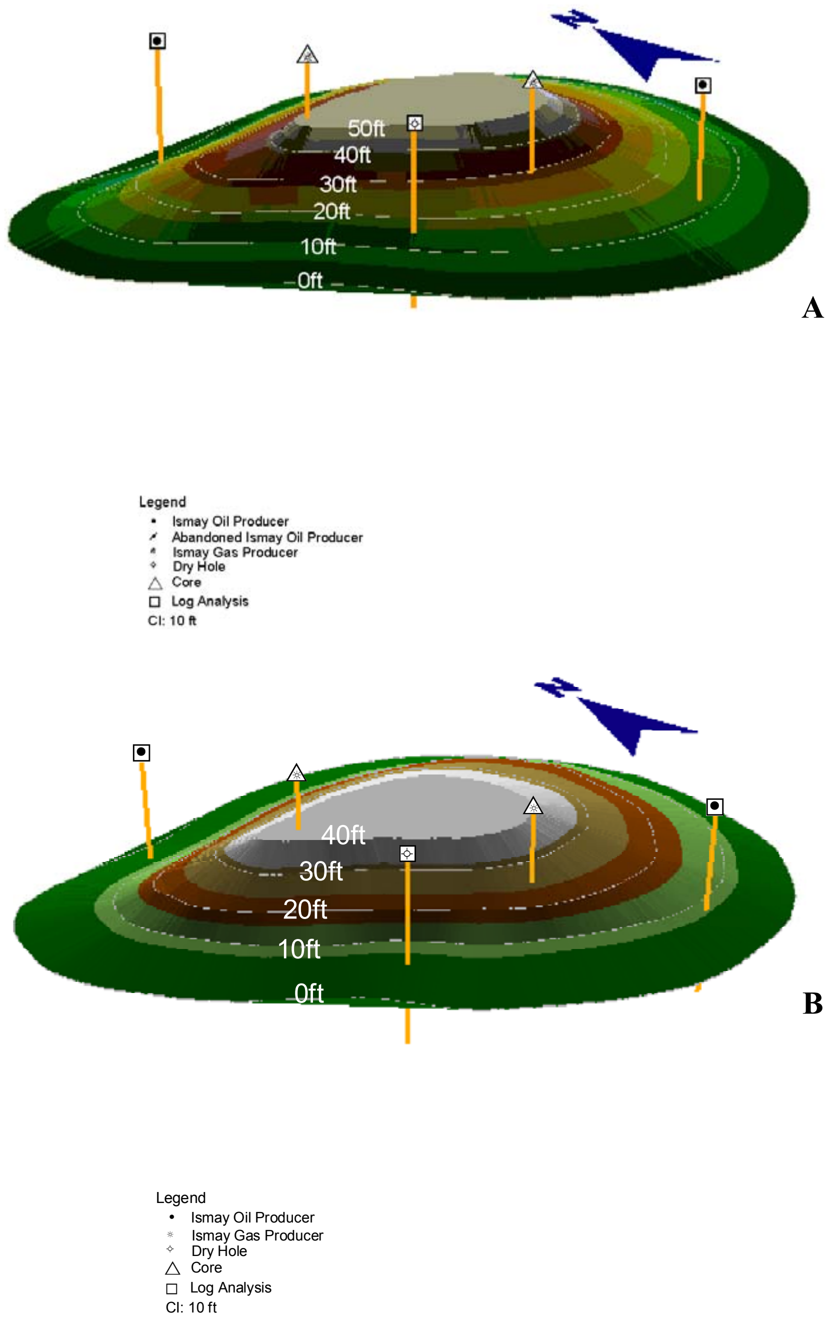
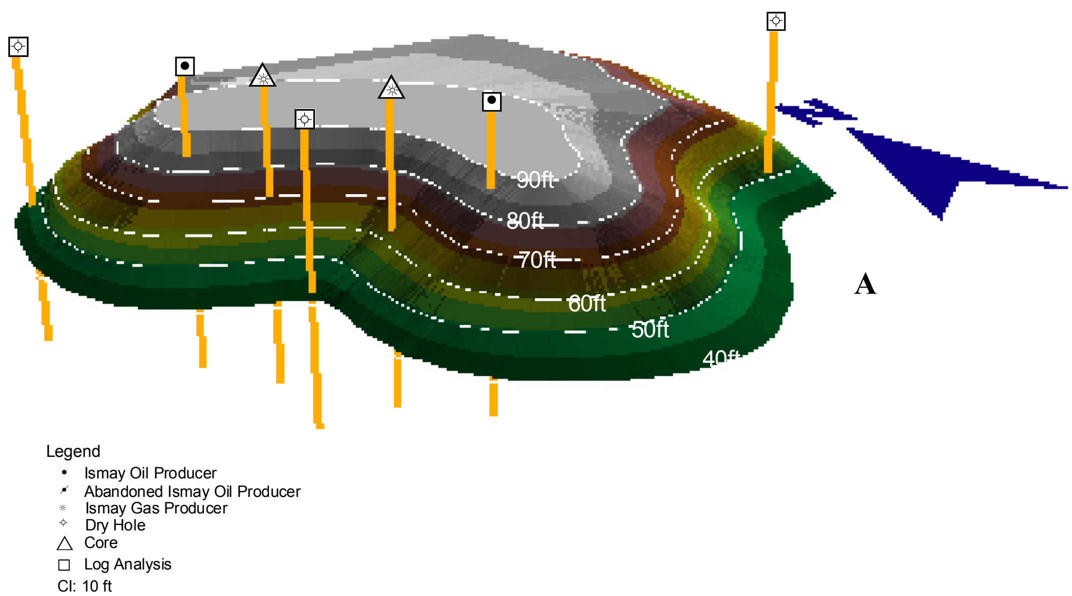


Figure 20. Three-dimensional models, upper Ismay zone net feet of porosity, as determined by geophysical log analysis, for greater than 10 percent porosity (A), and greater than 12 percent porosity (B), Cherokee field, San Juan County, Utah.



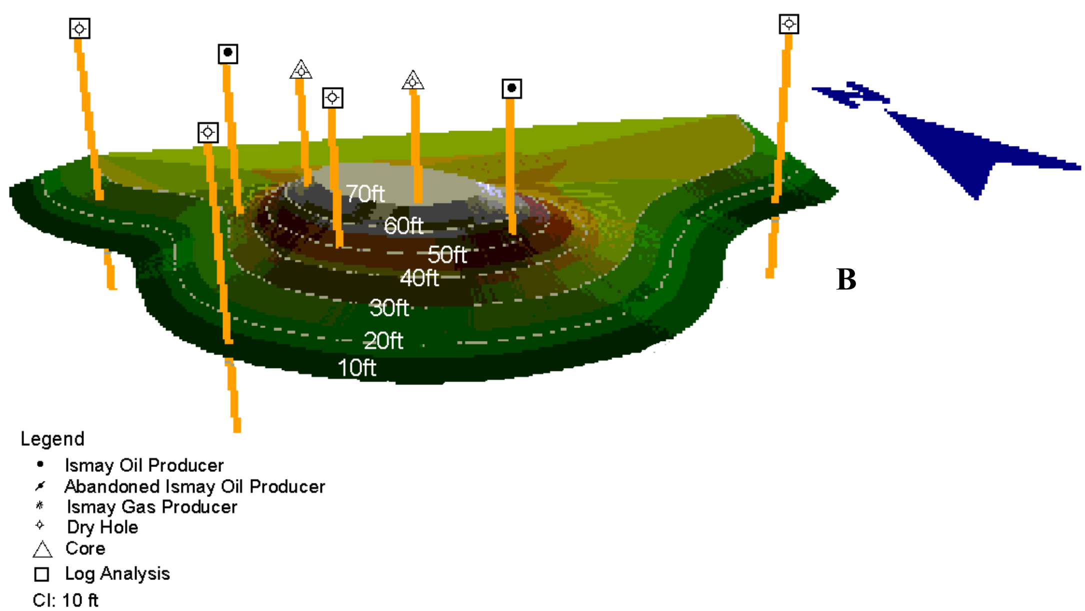


Figure 21. Three-dimensional models, upper Ismay zone net feet of limestone (A) and dolomite (B) as determined by geophysical log analysis, Cherokee field, San Juan County, Utah.

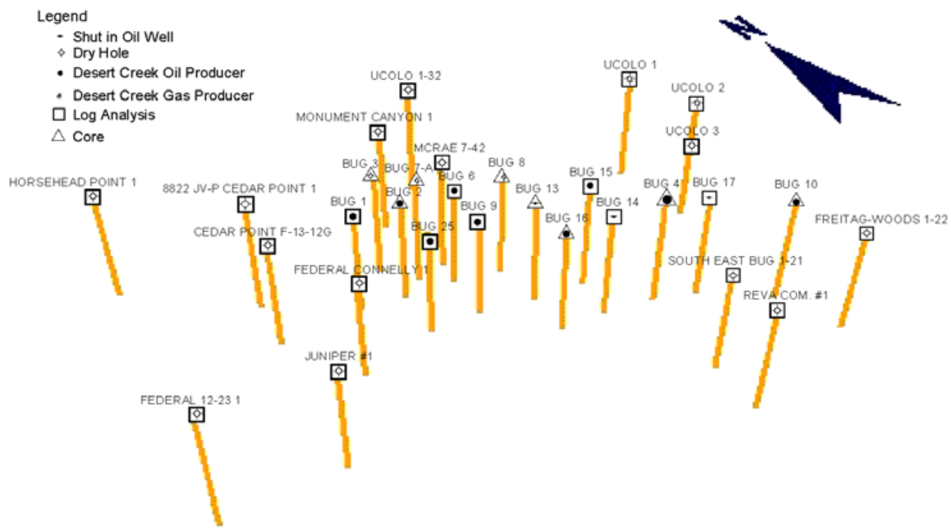


Figure 22. Relative locations and names of wells in the Bug field area, San Juan County, Utah.

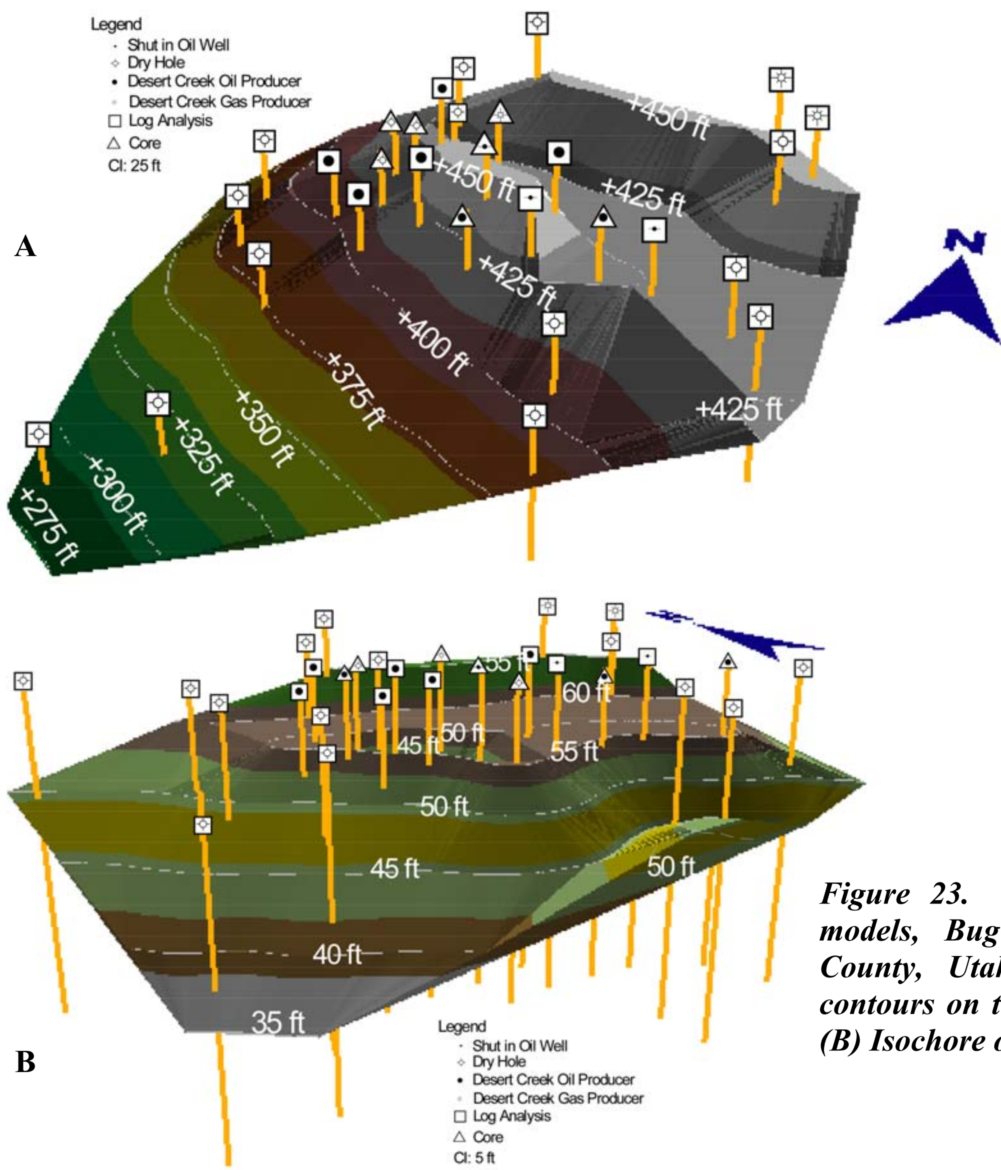


Figure 23. Three-dimensional models, Bug field, San Juan County, Utah. (A) Structure contours on top of Gothic shale. (B) Isochore of Gothic shale.

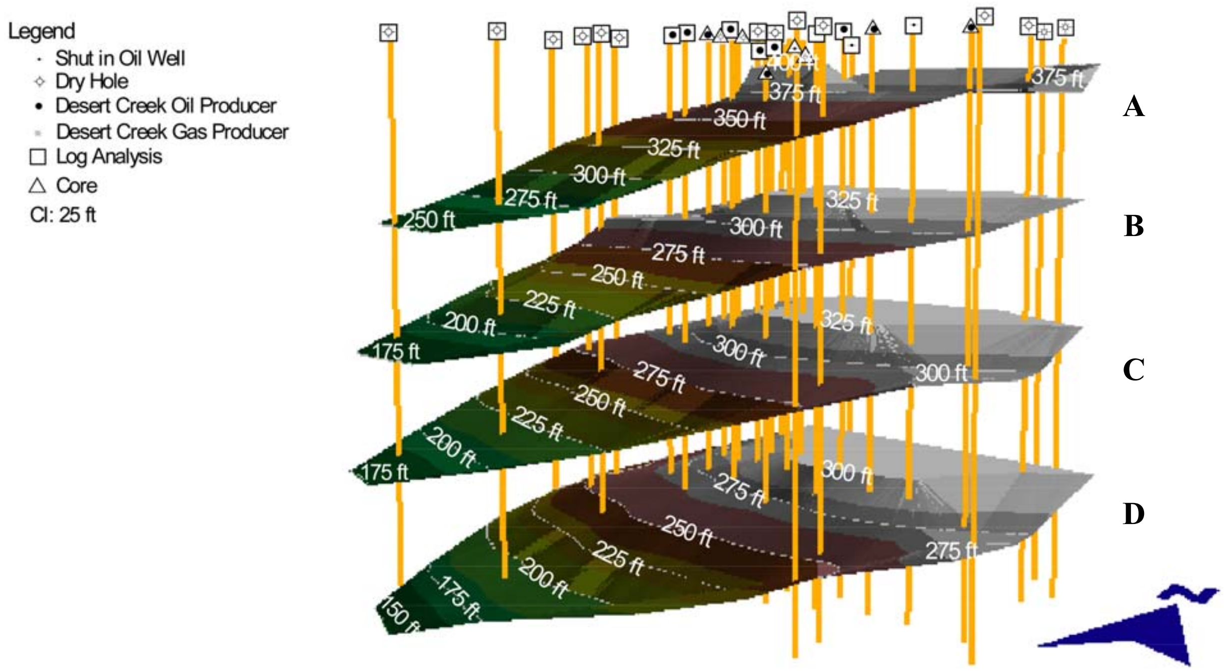


Figure 24. Three-dimensional models vertically stacked (no scale) with structural contours on tops of the Desert Creek zone (A), lower Desert Creek mound (B), lower Desert Creek clean carbonate (C), and Chimney Rock shale (D), Bug field, San Juan County, Utah.

Likewise, a 3-D model of the entire thickness of the Desert Creek zone (figure 25) also displays the same general northwest to southeast trend as does the structural diagram, with elongate thins and thicks. Bug field is located adjacent to one of the thin areas (70 feet [23 m]), but is not situated entirely on a thick. However, the Bug No. 6 well does contain the thickest section of Desert Creek in the mapped area at 138 feet (46 m).

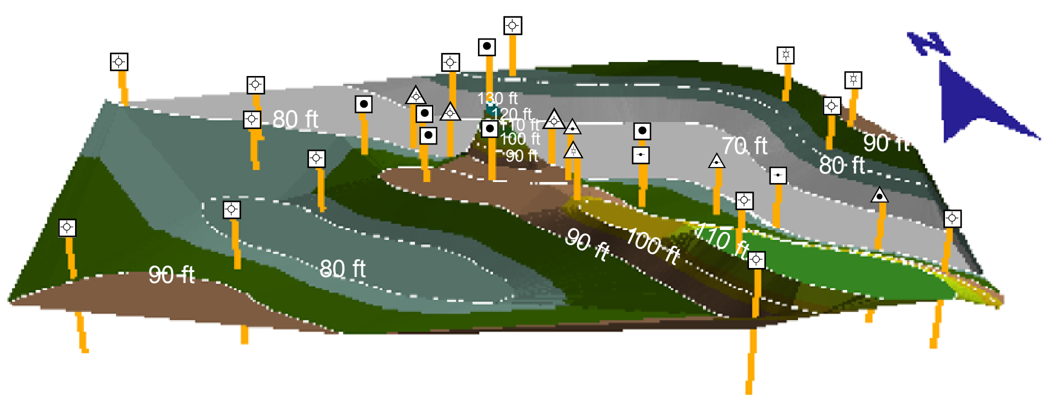


Figure 25. Three-dimensional model of the isochore of the Desert Creek zone, Bug field, San Juan County, Utah.

There is one anhydrite unit in the lower Desert Creek zone (figure 26). It displays the general northwest-southeast linear trend corresponding to the trend of the Gothic shale and entire Desert Creek. The unit is a thin, widespread anhydrite of relatively uniform thickness that averages about 5 feet (1.5 m) over most of the area. Bug producing wells are located in a thicker part (up to 9 feet [3 m]) as seen in both isochore and inverted isochore diagrams (figures 26A and 26B), and the Southeast Bug 1-21 well contains an exceptionally thick section of anhydrite at 18 feet (6 m). Unlike the Ismay zone, there are no intrashelf basins that we have identified in the Desert Creek (Eby and others, 2003a, 2003b).

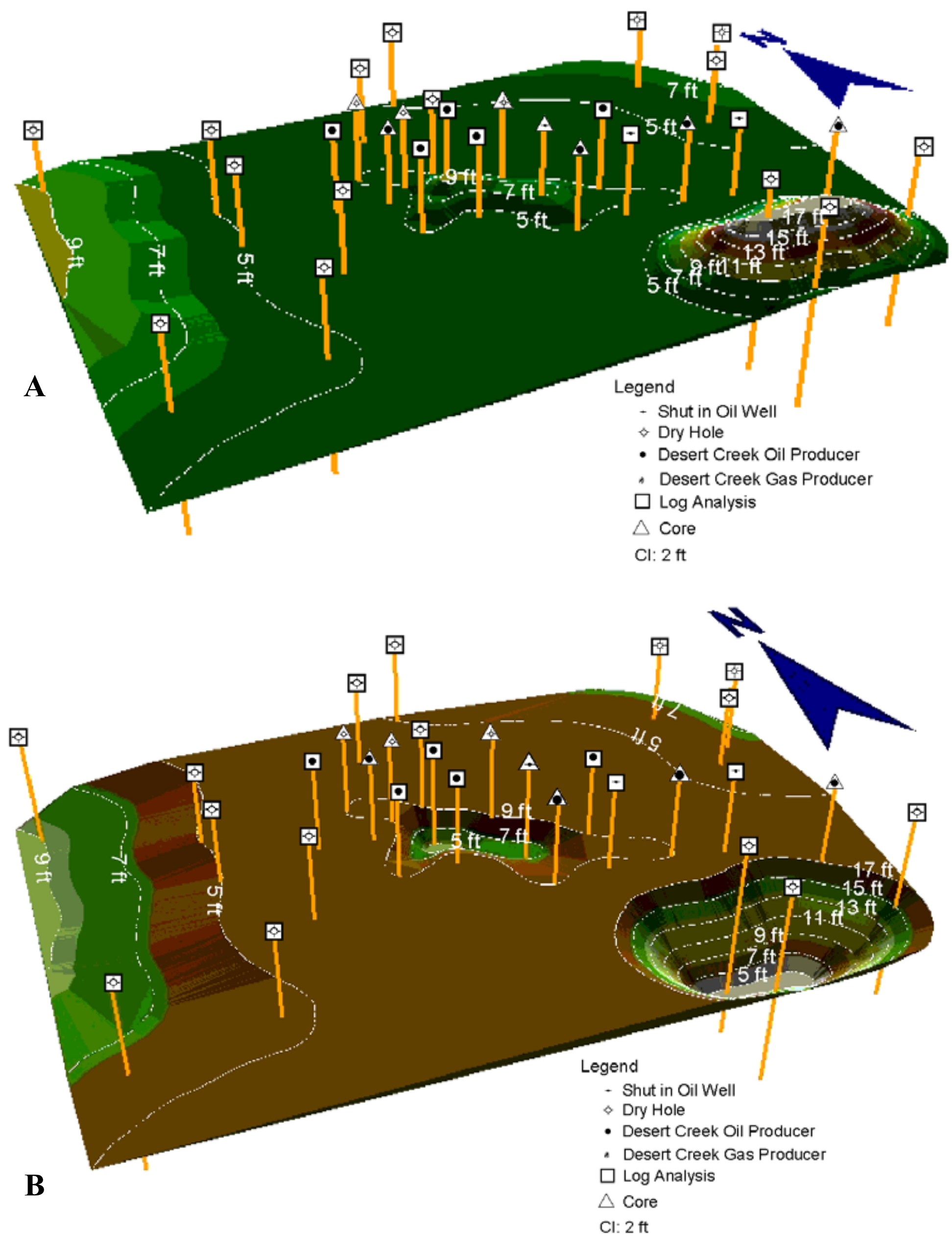


Figure 26. Three-dimensional models, Bug field, San Juan County, Utah. Lower Desert Creek zone anhydrite isochore (A) and inverted isochore (B).

The 3-D models of the thickness of the lower Desert Creek clean carbonate (figure 27) and mound core (figure 28) display an elongate, northwest-southeast-trending carbonate buildup depicting the typical, nearshore, shoreline-linear facies tracts of the Desert Creek zone in the northern Blanding sub-basin. Both diagrams appear similar as they represent nearly the same interval of the lower Desert Creek – the producing reservoir. The slightly thicker clean carbonate displays a small saddle between two subsidiary buildups, whereas the mound core is represented by one uniformly thick buildup.

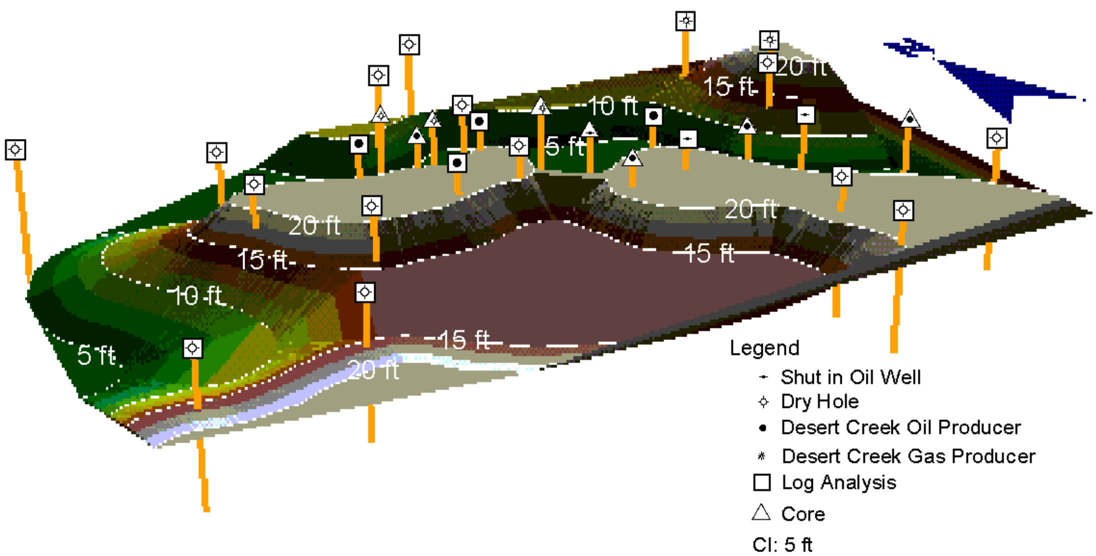


Figure 27. Three-dimensional model of the isochore of the lower Desert Creek zone clean carbonate, Bug field, San Juan County, Utah.

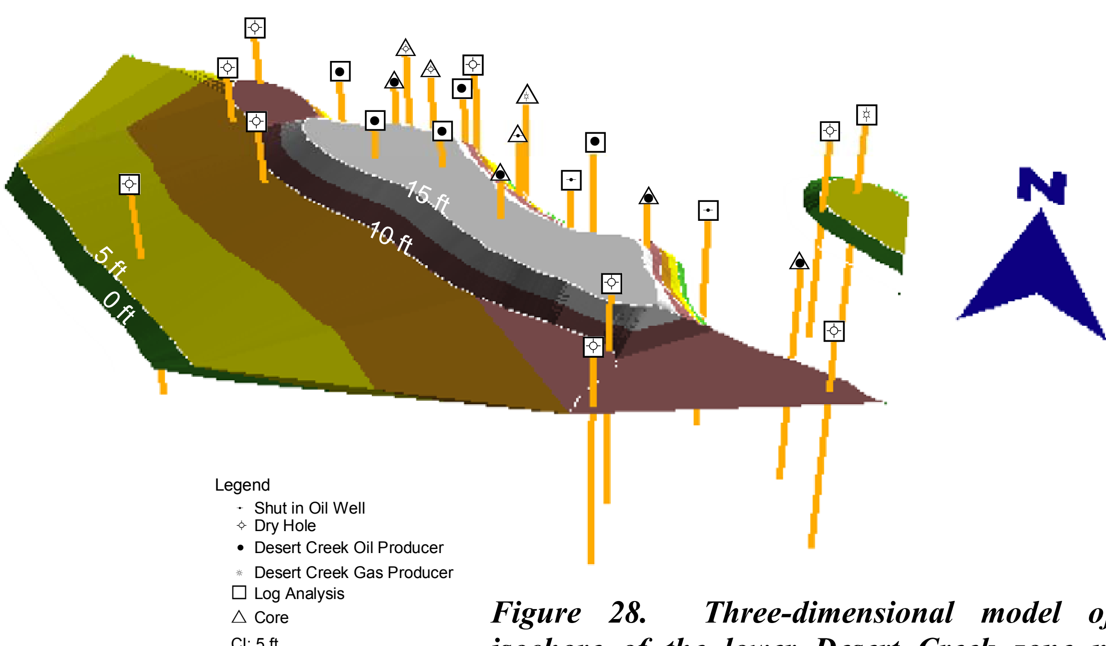


Figure 28. Three-dimensional model of the isochore of the lower Desert Creek zone mound core, Bug field, San Juan County, Utah.

The 3-D model of the thickness of the Chimney Rock shale (figure 29) shows a slightly east-west trend. The Chimney Rock varies in thickness only slightly over the area from 14 to 18 feet (5-6 m). Some Bug wells align along a subtle Chimney Rock thickness increase, but in general no particular pattern can be discerned.

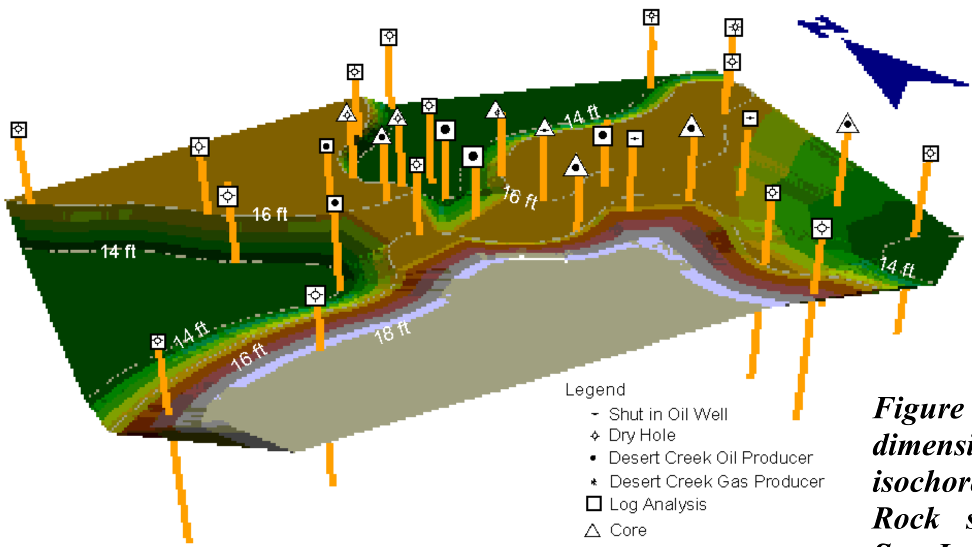


Figure 29. Three-dimensional model of the isochore of the Chimney Rock shale, Bug field, San Juan County, Utah.

The 3-D diagrams of the lower Desert Creek clean carbonate with the net feet of log-derived porosity greater than 10 and 12 percent (determined by geophysical log analysis; figures 30A and 30B) show an elongate reservoir buildup with two subsidiary thicks separated by a slightly thinner saddle that may represent an intermound trough. The northern thick trends generally east-west while the southern thick trends northwest-southeast. At 12 percent porosity, as expected the buildup is thinner and smaller in overall areal extent, but still mimics the general characteristics of the buildup at 10 percent porosity. In both diagrams the porosity pinches out along the northeast flank of the buildup, which when combined with a coincident anticline in the top of the lower Desert Creek zone clean carbonate (figure 24) provides a combination stratigraphic/structural trap. The 3-D diagrams of the lower Desert Creek clean carbonate with the net feet of core-derived porosity greater than 10 and 12 percent (determined by core analysis; figures 31A and 31B) also show an elongate reservoir buildup, but one that is narrower and thinner than its counterpart based on geophysical log analysis. No subsidiary buildups or saddles are present; the top of the buildup is flat. The buildup trends west-northwest to east-southeast. In both diagrams the entire carbonate buildup is bounded by a porosity pinchout and represents a stratigraphic trap.

The 3-D models of the lower Desert Creek clean carbonate with the net feet of core-derived permeability greater than 2 mD (figure 32A), greater than 10 mD (figure 32B), and greater than 50 mD (figure 32C), portray a buildup very similar to that constructed for net feet of porosity greater than 10 and 12 percent by core analysis (figures 31A and 31B). In both diagrams the entire carbonate buildup is defined by a permeability pinchout and trends west-northwest to east-southeast. At permeability greater than 2 mD (figure 32A), there is a subsidiary buildup in the northwestern part of the reservoir. At permeability greater than 10 and 50 mD (figures 32B and 32C), the thinner buildups depict two subsidiary thicks divided by an even thinner saddle.

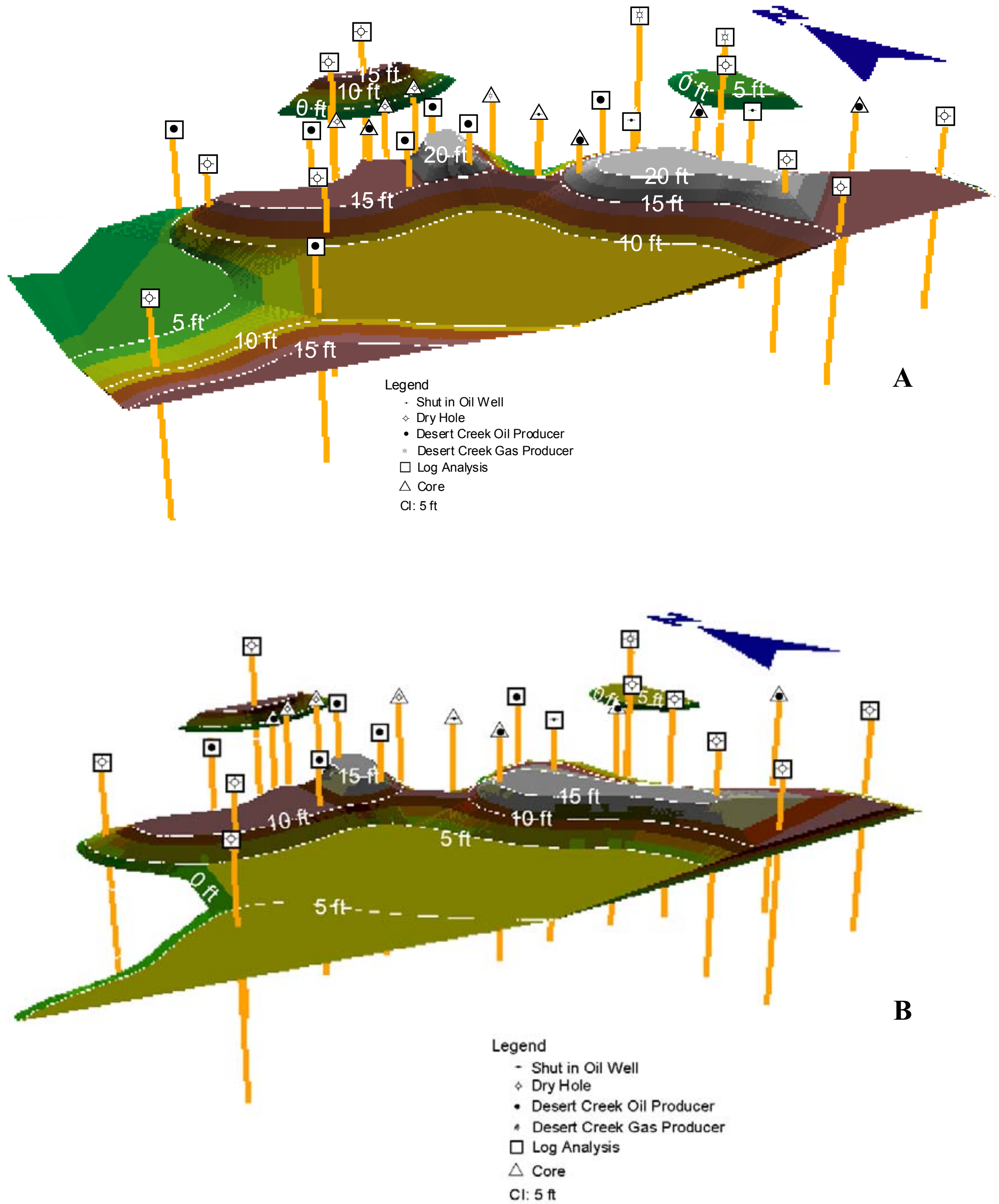


Figure 30. Three-dimensional models, lower Desert Creek zone clean carbonate net feet of porosity, as determined by geophysical log analysis, for greater than 10 percent porosity (A), and greater than 12 percent porosity (B), Bug field, San Juan County, Utah.

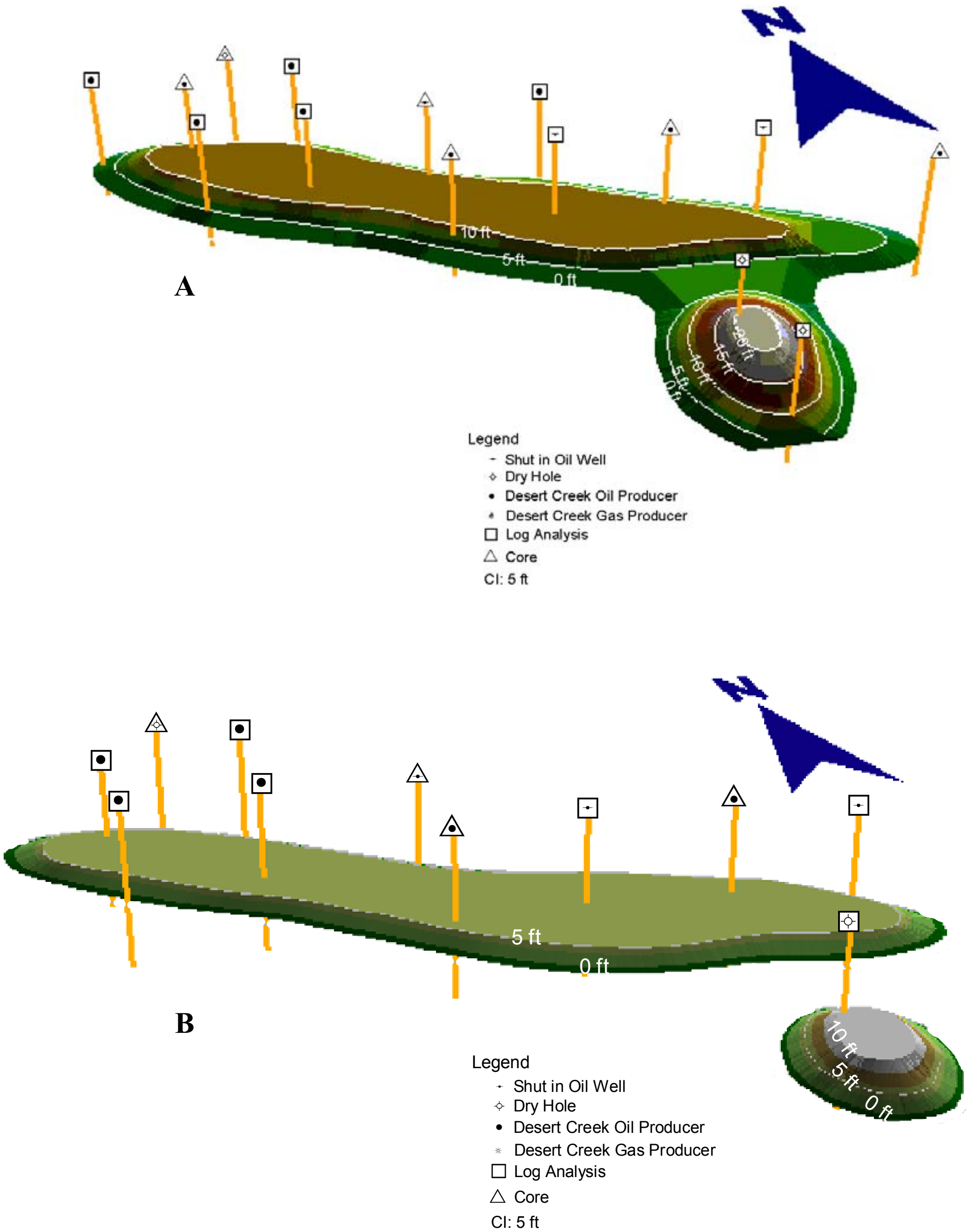


Figure 31. Three-dimensional models, lower Desert Creek zone clean carbonate net feet of porosity, as determined by core analysis, for greater than 10 percent porosity (A), and greater than 12 percent porosity (B), Bug field, San Juan County, Utah.

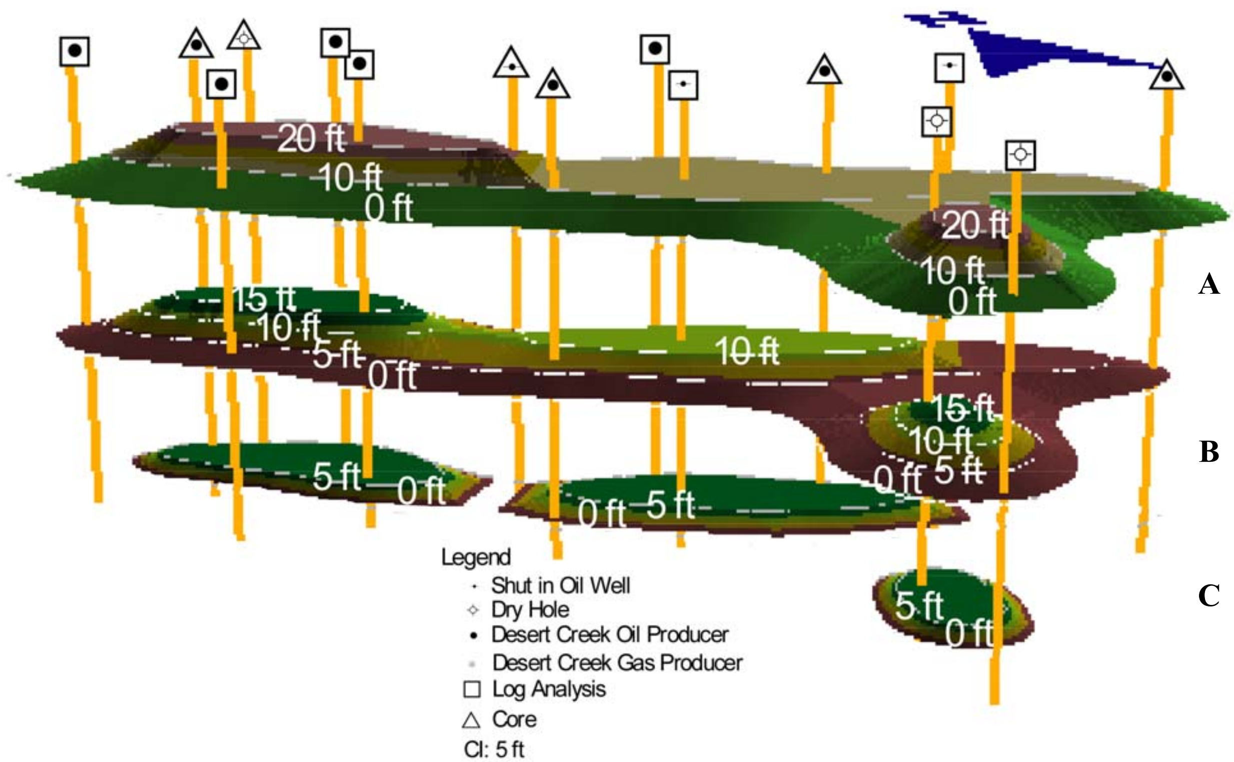


Figure 32. Three-dimensional models, lower Desert Creek zone clean carbonate net feet of permeability, as determined by core analysis, for greater than 2 mD (A), greater than 10 mD (B), and greater than 50 mD (C), Bug field, San Juan County, Utah.

Lower Desert Creek clean carbonate with net feet of dolomite (figure 33) was determined by core analysis. The extent of the 3-D diagram is limited due to the lack available cores in the area. Characteristic of the Desert Creek zone in the Blanding sub-basin, dolomite is the dominant lithology. The 3-D thickness diagram shows a large, northwest-southeast-trending buildup of dolomite within Bug field (figure 33). Not surprisingly, the buildup is divided into two subsidiary 30-foot- (10 m) thick areas separated by a saddle of 20 feet (7 m) thick.

RESERVE CALCULATIONS – RESULTS AND DISCUSSION

ArcView® was also used to calculate reservoir surface areas and volumes. Surface areas were measured along the slope of a surface, taking height into consideration. The surface area (feet squared) reported was that on the surface that falls above or below the specified height and converted to acres. The volume operation calculates the cubic space between a TIN surface and the horizontal plane located at the specified height. Volumes (cubic feet) were determined either above or below the plane. In the case-study fields, reservoir volumes were determined above planes representing the oil/water or high proved water contacts. Volumes were first converted to acre-feet and then oil and gas recovery factors (in barrels and MCF per acre-foot, respectively) were applied to calculate reserves (tables 2 and 3).

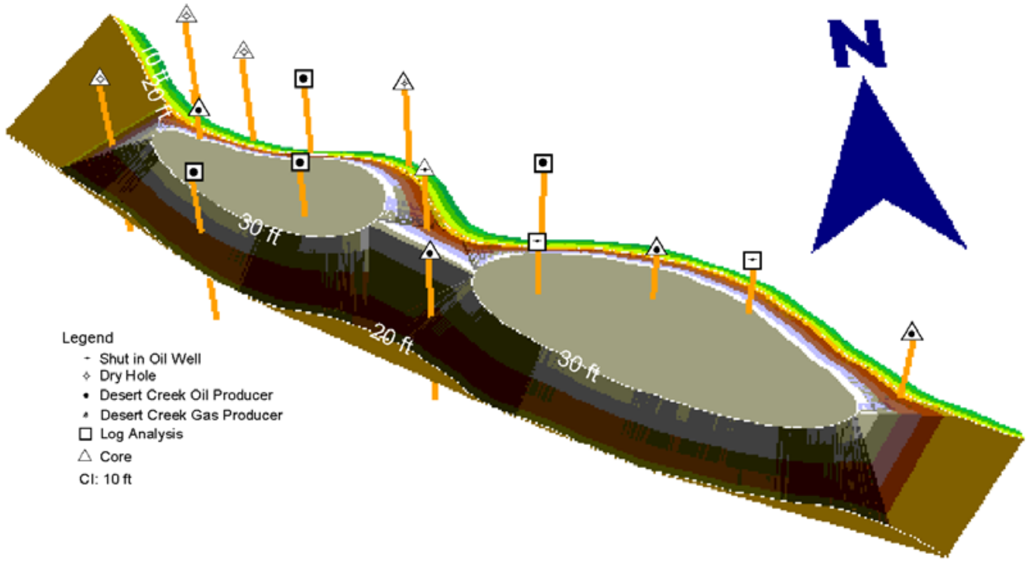


***Figure 33.** Three-dimensional model, lower Desert Creek zone clean carbonate net feet of dolomite, Bug field, San Juan County, Utah.*

Cherokee Field

Reservoir volumes (in acre-feet) (table 2) were calculated for porosity units 1 through 5 (figures 16 through 18) where the net feet of porosity was greater than 10 and 12 percent (figure 20). Recovery factors of 20 BO and 380 MCFG per acre-foot, respectively, were derived from Crawley-Stewart and Riley (1993). We applied these recovery factors to the various upper Ismay volumes to determine the primary oil and gas recovery volumes (table 2). Cumulative production as of January 1, 2004, was 182,464 BO and 3.67 BCFG (Utah Division of Oil, Gas and Mining, 2003). No single porosity unit can account for the volume of hydrocarbons produced. Therefore, all five or some combination of two or more porosity units are contributing, with porosity unit 5 being the largest followed by porosity unit 4, 2, 3, and 1 (table 2). The total volume of porosity units 1 through 5 (figure 18B) is 17,522 acre-feet, and this volume was calculated to contain over 350,000 BO and 6.6 BCFG primary recovery. Based on these calculations, the remaining recoverable oil and gas reserves are nearly 168,000 BO and 3 BCFG. Using a price of $30/bbl and $4/MCFG, the unrisked value of the remaining recoverable reserves is over $5 million and $11 million for oil and gas, respectively.

Extending the porosity cutoff down to porosity greater than 10 percent increases the combined volumes of porosity units 1 through 5 to 19,374 acre-feet, suggesting the presence of additional undrained zones (microporosity). This increase in reservoir volume amounts to an additional 37,000 BO and 0.7 BCFG that may be present in the upper Ismay zone in Cherokee field. However, our primary recovery volume for the net feet of porosity greater than 12 percent was less than the combined primary oil recovery volume of porosity units 1 through 5 as calculated earlier (table 2).

Table 2. Reservoir calculations, upper Ismay zone, Cherokee field, San Juan County, Utah.

NAME	VOLUME (AC FT)	OIL RECOVERY FACTOR (BBLS/AC FT)*	PRIMARY OIL VOLUME RECOVERY (BBLS)	GAS RECOVERY FACTOR (MCF/AC FT)*	PRIMARY GAS VOLUME RECOVERY (MCF)	CUMULATIVE FIELD OIL PRODUCTION (BBLS) AS OF 1/01/04*	REMAINING RECOVERABLE OIL (BBLS)	UNRISKED OIL VALUE BASED ON $30 PER BBL	CUMULATIVE FIELD GAS PRODUCTION (MCF) AS OF 1/01/04**	REMAINING RECOVERABLE GAS (MCF)	UNRISKED GAS VALUE BASED ON $4 PER MCF
Porosity Unit 1	699	20	13,975	380	265,528	ND	--	--	ND	--	--
Porosity Unit 2	4060	20	81,207	380	1,542,941	ND	--	--	ND	--	--
Porosity Unit 3	2117	20	42,348	380	804,607	ND	--	--	ND	--	--
Porosity Unit 4	4123	20	82,464	380	1,566,825	ND	--	--	ND	--	--
Porosity Unit 5	6523	20	130,454	380	2,478,620	ND	--	--	ND	--	--
Total of Porosity Units 1-5	17,522	20	350,448	380	6,658,521	182,464	167,984	$5,039,520	3,667,068	2,991,453	$11,965,812
Net Feet of Porosity (>10% by LA)	19,374	20	387,474	380	7,362,015	182,464	205,010	$6,150,300	3,667,068	3,694,947	$14,779,788
Net Feet of Porosity (>12% by LA)	14,650	20	293,001	380	5,567,017	182,464	110,537	$3,316,110	3,667,068	1,899,949	$7,599,796

*Crawley-Stewart and Riley, 1993.
**Utah Division of Oil, Gas & Mining, December 2003.
LA = log analysis
ND = no data

Table 3. Reservoir calculations, lower Desert Creek zone, Bug field, San Juan County, Utah.

NAME	VOLUME (AC FT)	OIL RECOVERY FACTOR (BBLS/AC FT)*	PRIMARY OIL VOLUME RECOVERY (BBLS)	GAS RECOVERY FACTOR (MCF/AC FT)*	PRIMARY GAS VOLUME RECOVERY (MCF)	CUMULATIVE FIELD OIL PRODUCTION (BBLS) AS OF 1/01/04**	REMAINING RECOVERABLE OIL (BBLS)	UNRISKED OIL VALUE BASED ON $30 PER BBL	CUMULATIVE FIELD GAS PRODUCTION (MCF) AS OF 1/01/04**	REMAINING RECOVERABLE GAS (MCF)	UNRISKED GAS VALUE BASED ON $4 PER MCF
Clean Carbonate Net Feet of Porosity (>10% by LA)	99,057	41	4,061,352	103	10,202,909	1,622,455	2,438,897	$73,166,910	4,483,368	5,719,541	$22,878,164
Clean Carbonate – Porosity Thickness (>10% by core analysis)	42,621	41	1,747,465	103	4,389,974	1,622,455	125,010	$3,750,300	4,483,368	0	0
Clean Carbonate Net Feet of Permeability (kh>2 mD)	64,027	41	2,625,105	103	6,594,775	1,622,455	1,002,650	$30,079,500	4,483,368	2,111,407	$8,445,628
Clean Carbonate Net Feet of Permeability (kh>10 mD)	41,746	41	1,711,568	103	4,299,794	1,622,455	89,113	$2,673,390	4,483,368	0	0

* Oline, 1996.
**Utah Division of Oil, Gas & Mining, December 2003.
LA = log analysis

Bug Field

Reservoir volumes were calculated for the lower Desert Creek zone clean carbonate at Bug field (table 3). These include volumes for net feet of porosity greater than 10 percent both by geophysical log analysis (figure 30A) and by core analysis (figure 31A), and volumes for net feet of permeability greater than 2 mD and 10 mD (figures 32A and 32B, respectively). Recovery factors of 41 BO and 103 MCFG per acre-foot, respectively, were derived from Oline (1996). We applied these recovery factors to the various lower Desert Creek clean carbonate volumes to determine the primary oil and gas recovery volumes (table 3). Cumulative production as of January 1, 2004, was 1,622,455 BO and 4.48 BCFG (Utah Division of Oil, Gas and Mining, 2003).

The volume calculated for net feet porosity greater than 10 percent by log analysis (99,057 acre-feet) is over twice that by core analysis (42,621 acre-feet). This may be a function of more data provided by well logs than by core, or that porosity determined from geophysical well logs is considerably optimistic. This suggests the presence of additional undrained zones (micro-box-work porosity). The bottom line is that from log analysis, the lower Desert Creek clean carbonate may contain recoverable oil and gas reserves of nearly 2,440,000 BO and 5.7 BCFG. Again, using prices of $30/BO and $4/MCFG, the unrisked value of the remaining reserves is over $73 million and $22 million for oil and gas, respectively. However, for the porosity volume calculated from core analysis, only about 125,000 BO remain having an unrisked value of $3.75 million. Theoretically, there are no remaining gas reserves using the calculated volume.

The volumes calculated for net feet of permeability also show significant differences (table 3). As expected, the net feet greater than 2 mD yielded an optimistically high volume (64,027 acre-feet) with remaining recoverable reserves of 1,000,000 BO and 2.1 BCFG, at an unrisked value of $30 million and $8.4 million, respectively. At 10 mD, the clean carbonate volume was a third lower (41,746 acre-feet) than at 2 mD, with about 89,000 BO at an unrisked value of $2.7 million. Again, theoretically, there are no remaining gas reserves using the calculated volume.

TECHNOLOGY TRANSFER

The UGS is the Principal Investigator and prime contractor for three petroleum-research projects, including two in the Paradox Basin. These projects are designed to improve recovery, development, and exploration of the nation's oil and gas resources through use of better, more efficient technologies. The projects involve detailed geologic and engineering characterization of several complex heterogeneous reservoirs. The Class II Oil Revisit project, described in this report, includes a practical oil-field demonstration of selected technologies in the Paradox Basin. The second Paradox Basin project will evaluate exploration methods and map regional facies trends for independents interested in the Mississippian Leadville Limestone play. The third project is part of the DOE Preferred Upstream Management Practices (PUMP II) program. That project, titled *Major Oil Plays in Utah and Vicinity*, will describe and delineate oil plays in the Utah/Wyoming thrust belt, Uinta Basin, and Paradox Basin. The DOE and multidisciplinary teams from petroleum companies, petroleum service companies, universities, private consultants, and state agencies are assisting with the three projects.

The UGS intends to release selected products of the Class II Oil Revisit Paradox Basin project in a series of formal publications. These publications may include data, as well as the results and interpretations. Syntheses and highlights will be submitted to refereed journals, as appropriate, such as the *American Association of Petroleum Geologists (AAPG) Bulletin* and *Journal of Petroleum Technology*, and to trade publications such as the *Oil and Gas Journal*. This information will also be released through the UGS periodical *Survey Notes* and be posted on the UGS Paradox Basin project Web page.

The Technical Advisory Board advises the technical team on the direction of study, reviews technical progress, recommends changes and additions to the study, and provides data. The Technical Advisory Board is composed of 13 field operators from the Paradox Basin (Seeley Oil Co., Legacy Energy Corp., Pioneer Oil & Gas, Hallwood Petroleum Inc., Dolar Oil Properties, Cochrane Resources Inc., Wexpro Co., Samedan Oil Corp., Questar Exploration, Tom Brown Inc., PetroCorp Inc., Stone Energy LLC., and Sinclair Oil Corp.). This board ensures direct communication of the study methods and results to the Paradox Basin operators. The Stake Holders Board is composed of groups that have a financial interest in the study area including representatives from Utah and Colorado state governments (Utah School and Institutional Trust Lands Administration; Utah Division of Oil, Gas and Mining; and Colorado Oil and Gas Conservation Commission), Federal Government (U.S. Bureau of Land Management and U.S. Bureau of Indian Affairs), and the Ute Mountain Ute Indian Tribe. The members of the Technical Advisory and Stake Holders Boards receive all semi-annual technical reports and copies of all publications, and other material resulting from the study.

Utah Geological Survey *Survey Notes* and Web Site

The purpose of *Survey Notes* is to provide non-technical information on contemporary geologic topics, issues, events, and ongoing UGS projects to Utah's geologic community, educators, state and local officials and other decision makers, and the public. *Survey Notes* is published three times yearly. Single copies are distributed free of charge and reproduction (with recognition of source) is encouraged. The UGS maintains a database that includes those companies or individuals (more than 300 as of April 2004) specifically interested in the Paradox Basin project or other DOE-sponsored UGS projects. They receive *Survey Notes* and notification of project publications and workshops.

The UGS maintains a Web site, http://geology.utah.gov. The UGS site includes a page under the heading *Economic Geology Program*, which describes the UGS/DOE cooperative studies past and present (Paradox Basin, Ferron Sandstone, Bluebell field, Green River Formation, PUMP II), and has a link to the DOE Web site. Each UGS/DOE cooperative study also has its own separate page on the UGS Web site. The Paradox Basin project page http://geology.utah.gov/emp/Paradox2/index.htm contains: (1) a project location map, (2) a description of the project, (3) a list of project participants and their postal addresses and phone numbers, (4) a reference list of all publications that are a direct result of the project, (5) semi-annual technical progress reports, and (6) project technical poster displays.

Technical Presentations

The following technical presentations were made during the second six months of the fourth project year as part of the technology transfer activities:

"Heterogeneous Shallow-Shelf Carbonate Buildups in the Blanding Sub-Basin of the Paradox Basin, Utah and Colorado: Targets for Increased Oil Production & Reserves Using Horizontal Drilling Techniques" by Thomas C. Chidsey, Jr., American Association of Petroleum Geologists Student Chapter Meeting, University of Utah, Salt Lake City, Utah, January 23, 2004. Core photographs, SEM, pore casts, photomicrographs, capillary/mercury injection graphs, maps, diagenetic analysis, and horizontal drilling recommendations were part of the presentation.

"Regional Facies Trends in the Upper Ismay Zone of the Blanding Sub-basin of the Paradox Basin, Utah" by David E. Eby, at the Society for Sedimentary Geology (SEPM), Rocky Mountain Section Luncheon Meeting, Denver, Colorado, March 30, 2004. Core photographs of facies types, regional facies maps, and horizontal drilling recommendations were part of the presentation.

Project Publications

Chidsey, T.C., Jr., McClure, Kevin, Morgan, C.D., Eby, D.E., and Nelson, S.T., 2003, Heterogeneous shallow-shelf carbonate buildups in the Paradox Basin, Utah and Colorado: targets for increased oil production and reserves using horizontal drilling techniques – semi-annual technical progress report for the period April 6, 2003 to October 5, 2003: U.S. Department of Energy, DOE/BC15128-7, 40 p.

Eby, D.E., 2004, Regional facies trends in the upper Ismay zone of the Blanding sub-basin of the Paradox Basin, Utah [abs.]: Society for Sedimentary Geology (SEPM), Rocky Mountain Section Newsletter, v. 29, no. 6, p. 1 and 3.

CONCLUSIONS

The Blanding sub-basin within the Pennsylvanian Paradox Basin developed on a shallow-marine shelf that locally contained algal-mound and other carbonate buildups. The two main producing zones of the Paradox Formation are the Ismay and the Desert Creek. The Ismay zone is dominantly limestone comprising equant-shaped buildups of phylloid-algal material. The Desert Creek zone is dominantly dolomite comprising regional nearshore-shoreline trends with highly aligned, linear facies tracts. This study was undertaken to provide a useful database and methodology for identifying potential horizontal drilling targets within heterogeneous carbonate rocks containing porous phylloid-algal buildups and associated facies. The 3-D models were created using ESRI ArcView® 3D Analyst. Structure, isochore, and other reservoir property contour maps were digitized using AutoCad®, then brought into ArcView®.

Cherokee field 3-D diagrams with structural contours on top of the upper and lower Ismay zone, upper Ismay clean carbonate, and Gothic shale show the same general southwest-dipping structural nose upon which the carbonate buildup developed. The abrupt termination of the structure suggests the possible presence of a northwest-southeast-trending normal fault where late-stage microporosity may have developed. Two anhydrite units in the upper Ismay zone display a similar west-northwest to east-southeast linear trend as the Hovenweap and

Gothic shales. Cherokee wells that contain phylloid-algal buildups lie along the edge of thick anhydrite and follow the regional upper Ismay facies pattern where intrashelf basins are the locations of thick anhydrite accumulations. Phylloid-algal buildups developed on innershelf and tidal flats within curvilinear bands that rim the intrashelf basins. The 3-D models of the thickness of the entire Ismay zone, upper Ismay, lower Ismay, and upper Ismay clean carbonate, display a general west-northwest to east-southeast trend punctuated by elongate to slightly equant thicks. Five reservoir porosity units with porosity greater than 6 percent are present in the upper Ismay mound separated by low-porosity/permeability barriers. These high-porosity units represent the phylloid-algal buildups and, typical of the upper Ismay trend in the Blanding sub-basin, are viewed in 3-D as small equant-shaped pods. Porosity unit 5 is the largest and most likely the major production contributor, as well as holding the bulk of the remaining reserves. The 3-D thickness diagrams suggest all five porosity units have an untested northeastern area. The 3-D thickness of net feet of limestone and dolomite show a large buildup of both limestone adjacent and dolomite within Cherokee field. Characteristic of the Ismay zone in the Blanding sub-basin, limestone is the dominant lithology. However, there is an unusual amount of dolomite present. In both cases, a carbonate buildup continues northeast of the present field wells.

Bug field 3-D diagrams with structural contours on top of the Desert Creek zone, lower Desert Creek mound, lower Desert Creek clean carbonate, and Chimney Rock shale each show southwest regional dip and a subtle, elongate, northwest-southeast-trending anticline. A 3-D model of the entire thickness of the Desert Creek zone likewise displays the same general northwest-southeast trend, as do the structural diagrams, with elongate thins and thicks. The 3-D models of the thickness of the lower Desert Creek clean carbonate and mound core display an elongate, northwest-southeast-trending carbonate buildup depicting the typical, nearshore, shoreline-linear facies tracts of the Desert Creek zone in the northern Blanding sub-basin. The 3-D diagrams of the lower Desert Creek clean carbonate with log-derived net feet of porosity greater than 10 and 12 percent show an elongate reservoir buildup with two subsidiary thicks separated by a slightly thinner saddle that may represent an intermound trough. In both diagrams, the porosity pinches out along the northeast flank of the buildup, which, when combined with the coincident anticlinal structure on the top of the lower Desert Creek zone clean carbonate, provides a combination stratigraphic/structural trap.

Reservoir volumes (in acre-feet) were calculated for the Cherokee and Bug fields. Recovery factors of 20 BO and 380 MCFG per acre-foot, respectively, were used for Cherokee field to determine the upper Ismay primary oil and gas recovery. The total volume of porosity units 1 through 5 is 17,522 acre-feet, and may contain over 350,000 BO and 6.6 BCFG primary recovery. Based on these calculations, the remaining recoverable oil and gas reserves are nearly 168,000 BO and 3 BCFG, suggesting the presence of additional undrained zones (microporosity). Using a price of $30/bbl and $4/MCFG, the unrisked value of the remaining recoverable reserves is over $5 million and $11 million for oil and gas, respectively.

Recovery factors of 41 BO and 103 MCFG per acre-foot, respectively, were used for Bug field to determine the lower Desert Creek clean carbonate primary oil and gas recovery. The volume calculated for net feet of reservoir with porosity greater than 10 percent by log analysis is 99,057 acre-feet. This suggests the presence of additional undrained zones (micro-box-work porosity). The lower Desert Creek clean carbonate may contain recoverable oil and gas reserves of nearly 2,440,000 BO and 5.7 BCFG. Again, using $30/BO and $4/MCFG, the unrisked value of the remaining reserves is over $73 million and $22 million for oil and gas, respectively.

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